Methods of Assessing Utilisable Sawlog Volume of Riparian Alien Invasive Forests in the Western Cape Province of South Africa

by

Brendan Nicholas Marais

Thesis presented in fulfilment of the requirements for the degree of Master of Science in Forestry and Wood Science at the Faculty of AgriSciences, Department of Forest and Wood Sciences, Stellenbosch University

Supervisors: Dr David Drew, Mr Cori Ham

March 2018

Declaration

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Abstract

Alien invasive plant (AIP) species pose a significant threat to biodiversity, water security and agricultural resources. Several river courses in the Western Cape province of South Africa experience a severe problem with AIPs. Working for Water, a government initiative established in 1995 (now part of the Department of Environmental Affairs [DEA] under Natural Resources Management [NRM]), has identified the Berg River as particularly problematic with biomass ear-marked for clearing. To date, NRM has cleared nearly 3 million hectares of AIPs and creates 20 000 jobs per annum.

The Value-Added Industries (VAI) Programme has been created in an attempt to extract value from cleared biomass instead of leaving it in-field. This study presents an inventory of riparian alien invasive forests (AIFs) focussing on a method of measuring utilisable sawlog volume for the production of wooden school desks. The results of the sawlog inventory are presented with a type of correction factor, correcting for measured decreases in utilisable volume resulting from deviant stem form. The correction factor is a comparison between conventionally derived standing volume and more in-depth measurements of tree-level variables for estimates of higher value sawlogs over five diameter classes at breast height (DBH) classes, for two AIP species (*Eucalyptus camaldulensis* and *Acacia mearnsii*) present on the study site.

Stem height at first major branching was measured and assessed in the first step of determining the correction factor. Thereafter, stem taper was assessed by measuring diameter at breast height and upper stem diameter at first major branching. This was compared to conventional equations used to derive upper stem diameter at first major branching for a tree of given DBH. Lastly, stem sweep was measured and assessed. The Simsaw 6 software package was used to conduct sawing simulations to acquire insight into the possible range of sawn product volume recovery attainable from AIFs as well as in the creation of the so called sawlog volume creation factor (SVCF) through the input of sawlog dimensions and subsequent volume calculation thereof.

The results showed that height at first major branching influenced sawlog volume recoverable from the AIF site with stem taper not featuring as a variable of interest. Furthermore, the presence of stem sweep influenced sawn product volume recovery compared to logs with no sweep.

The results of this study are expected to feed into NRM's Management Unit Clearing Plan (MUCP); software developed for the purposes of visualising the extent of invasion density and the subsequent operations and costs thereof required to clear areas of AIPs completely.

Opsomming

Uitheemse indringer plant spesies (AIP) veroorsaak ‘n beduidende bedreiging vir biodiversiteit, water-sekerheid en landbou hulpbronne. Verskeie rivierlope in the Wes Kaap Provinsie in Suid Afrika ondervind tans erge probleme met indringer plante. Werk vir Water (Working for Water), ‘n staatsprogram, gevestig in 1995, wat nou deel uitmaak van Departement van Omgewingsake (DEA) en tans resorteer onder Natuurlike Hulpbronne Bestuur (NRM), het die Bergrivier geïndentifiseer as uiters problematies met heelwat biomassa wat verwyder moet word. Tot op hede is bykans 3 miljoen hektaar indringer plante verwyder deur NRM en skep hierdie projek ongeveer 20 000 werksgeleenthede per jaar.

Die Toegevoegde Waarde Industriële Program, (VAI Programme) is geskep in ‘n poging om waarde uit hierdie uitgekapte biomassa te haal instede daarvan om dit op-veld agter te laat. Hierdie navorsing studie bied ‘n opsomming van rivierlangs uitheemse indringer bos met die fokus op die metodiek van meting van bruikbare saag volumes wat aangewend kan word om skoolbanke te produseer. Die resultate van die bruikbare saag volumes word voorgele met ‘n regstellende faktor (correction factor), die resultaat van verminderende volumes bruikbare hout weens kromgetrekte stamme. Die regstellende faktor is wiskundig bepaal na aanleiding van die vergelyking van konventionele geplante volumes teenoor meer spesifieke meting van boom-vlak variasies vir skattings van hoe-waarde saag volumes oor 5 diameter klasse op borshoogte (DBH). Gemeet vir twee AIP spesies, naamlik, *Eucalyptus camaldulensis* and *Acacia mearnsii* wat op die ondersoek terrein voorkom.

Stamhoogte by die eerste vertakking was gemeet en ge-evalueer as die eerste stap in die bepaling van die regstellende faktor. Daarna is stamspitsing (taper) bepaal deur meting van DBH en dan die boonste stamdiameter by eerste hoofvertakking. Hierdie waardes is dan vergelyk met normale berekeninge om boonste stamdiameters op eerste hoofvertakkings te bereken vir bome met gegewe DBH. Laastens is stamkurwe gemeet en ge-evalueer. Die Simsaw 6 sagteware is aangewend om saagmeul simulasie te doen om der halwe resultate te lewer oor moontlike gesaagte produk volumes wat bekom sal word van AIFs. Dit het ook tot die skep van die genoemde “sawlog volume correction factor” (SVCF) of te wel “saagblok volume regstellende faktor” [SVRF] gelei na aanleiding van saagblok mates en afgeleide volume berekeninge wat daaruit gevloei het.

Die resultate toon dat hoogte op eerste hoof vertakking wel ‘n invloed het op saagblok volumes wat herwin word van AIFs terwyl stamspitting minimale invloed het op finale resultate. Verder is gevind dat aanwesigheid van stamkurwe die finale volumes negatief be-ïnvloed teenoor stamme met geen kurwes.

Die resultate van hierdie ondersoek behoort deel te vorm van NRM se toekomstige “Management Unit Clearing Plan” (MUCP); die ontwikkelde sagteware wat ten doel het om te help met visualisering van indringer digtheid en sal bydra tot koste-bepaling van skoonmaak operasies wat benodig word om AIPs totaal te verwyder.

Acronyms

AIP	Alien Invasive Plant
AIF	Alien Invasive Forest
DEA	National Department of Environmental Affairs
WfW	Working for Water
NRM	Natural Resources Management
VAI	Value-added Industries
DSS	Decision-Support System
FAO	Food and Agriculture Organisation of the United States
TLS	Terrestrial LiDAR Scanning
GNSS	Global Navigation Satellite System
REDD+	Reducing Emissions from Deforestation and Forest Degradation
STPH	Stems per hectare
DBH	Diameter at breast height
BA	Basal area
SVCF	Sawlog Volume Correction Factor
MUCP	Management Unit Clearing Programme
GIS	Geographical Information System
QGIS	Quantum Geographical Information System
SfM	Structure from Motion
CSIR	Council for Scientific and Industrial Research
ACS	Angle Count Sampling

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Chapter 1: Introduction

1.1 Background

Since the mid-seventeenth century (1650), some 9000 foreign plant species have been introduced to South Africa (Nyoki, 2003). Many of them have been intentionally introduced for various agricultural and forestry purposes (Richardson, 1998). The use of such foreign trees species in commercial forestry for roundwood and pulp production has led to the rapid expansion of global forests in the twentieth century, particularly in developing countries such as South Africa (Zobel, et al., 1987).

Unfortunately, the introduction of foreign species has some negative consequences (timber production and the contribution to GDP are positive). Approximately 200 of the introduced species in South Africa have been classified as invasive and can out-compete indigenous species (Henderson, 2001), creating a significant threat to the country's biological biodiversity (DEA, 2016). AIPs (AIPs) affect ecological health, water security, productive use of land, and economic development (DEA, 2016) and include many terrestrial and fresh-water trees and shrubs (Agricultural Research Council, 2014).

In the past, the problem of AIPs in South Africa was seen only as an ecological problem affecting biodiversity (Enright, 2000). Governmental efforts to reduce the numerous negative effects of AIPs (not only on biodiversity) have seen the creation of the Working for Water (WfW) programme, now called Natural Resources Management (NRM). NRM is a government initiative headed up by the Department of Environmental Affairs (DEA) and is primarily concerned with ensuring the conservation of water and biological resources through combating the threat of AIPs, animals and microbes (DEA, 2016). NRM has been responsible for the clearing of AIPs from mountain catchments, while landowners themselves were responsible for the clearing of AIPs from their land, but new NRM priorities have meant this will now be a joint effort between landowners and government.

Public and politicians were not aware of the full effects of the AIP problem with special emphasis on the danger to lost water resources (Enright, 2000). A particular point of concern is the impact of encroachments in riverine systems, and the putative losses in outflows. For example, work by Le Maitre, et al. (1996) and van Wyk (1987) predicted increases in streamflow of 350 mm – 500 mm rainfall equivalent after the clearing of invasive plant species from a river course in the Western Cape province of South Africa.

Since 1995 the NRM initiative has cleared more than one million hectares of land occupied by AIP species. This has been achieved through the efforts of NRM officials, making use of mechanical, chemical, biological and integrated control methods. Every year, 20 000 people are provided with training and jobs. Of these, approximately 52% are women (DEA, 2016). However, in addition to these important objectives, a programme to utilise and add value to biomass from NRM clearing operations was initiated in 1998. This programme, called the Value-Added Industries (VAI) programme, seeks to develop small business enterprises promoting these businesses to operate either independently or as partnerships between public and private sectors. Some of the products the VAI programme produces includes bathroom accessories, lights and lamps, firewood, charcoal, decor items, and furniture (DEA, 2016).

The VAI programme has three main objectives (DEA, 2016):

- maximising the positive economic benefits of the WfW programme, by creating extra jobs through the harvesting and processing of plant material;
- reducing the net cost of clearing, thereby contributing to the sustainability of the WfW programme,
- minimising potential negative environmental impacts, such as fire damage, by leaving less biomass behind after clearing

A variety of products can be extracted from a forest of "invasive" trees. While these products, like charcoal or fuelwood, are potentially high value products, they are not necessarily the best use if timber quality is suitable for higher value wood products like furniture which requires processed timber (International Finance Corporation, 2017). If, however, a product requiring processing, like a school desk (which has been identified as a potential product stream), is to be produced from an alien invasive forest (AIF) stand (site), it is important to understand the structure of the forest and the efficiencies in sawing. It is timber of this sort that has been given primary consideration in this study. To this end, it is therefore necessary to be able to characterise and measure the trees to properly assess what might be extractable (van Laar & Theron, 2004).

An important aspect of being able to sustainably process the raw material into a set of specified products with particular properties requires knowing about (a) the amount of material on the ground to be harvested and (b) how much of that material is utilisable. Obtaining this information would require a forest inventory to include forest structure and tree form (condition) as variables. Tree height and diameter, site density (trees per hectare of forest land), as well as an assessment of species diversity and tree form characteristics will aid in the assessment of available utilisable material (van Laar & Akcha, 2007). While intensive forest assessments of alien invasive stands, even for high value projects might not necessarily be operationally feasible (due to the high costs of field data collection and processing), there is however still a need to increase the level of information currently available to inform harvesting and processing operations (Main, et al., 2016). This study contributes to increasing this understanding of how much volume of utilisable timber can be expected from a selected set of AIF types, specifically for the production of a range of finished wood products (school desks).

1.2 Problem statement: Need for AIP inventory

At present, approaches to characterising the amount of biomass available for product development, and the product options from invasive plant clearing operations are not very accurate. One issue that arises from this problem is the level of accuracy in terms of estimating economic feasibility, in terms of both costs of extraction and potential returns from sales of the extracted biomass (Mugido, et al., 2014).

The current assessment method employed depends on several different stand characteristics (e.g. tree size and site accessibility) and their interaction with the contractor carrying out the clearing operation (e.g. equipment, personnel and logistical limitations). Some trees exhibit diameters too large for conventional harvesting and transportation practices and some of these large trees are found in dangerously precarious positions along riverbanks making their successful extraction more difficult. Contractors make use of expensive, heavy-duty machinery and apply to NRM officials on a tender basis to clear the stipulated area of the invasive biomass. The contractors are paid per hectare of cleared biomass and in return are charged for the removed timber. This timber is priced per cubic metre of volume and discounted from the cost per hectare of harvesting (clearing) initially charged by the contractor (Wessel Wentzel, [Deputy Director: NRM Regional Operations and Planning, Western Cape Environmental Programmes], personal communications, 8 July, 2016).

The status quo assessment method makes reference to the necessity of a number of different attributes of an AIP site for its successful mapping. These attributes include area (ha), species classification, vegetation age, vegetation density, average slope, and accessibility index (e.g. driving and walking time to site). This AIP mapping is carried out using two techniques; (1) digitised orthphotography (scale-corrected aerial photography) combined with in-field data capture and verification, and (2) in-field GNSS mapping and data capture (Working for Water Programme, 2003).

There is however, information missing from such maps such as detailed stand characterisation which is necessary to accurately estimate above-ground biomass (Main, et al., 2016). The benefits to attaining such detailed information of AIP sites are extensive. Such information can assist in the process of valuing the AIP area and pricing its rehabilitation as it will give contractors responding to tenders by NRM an idea of the cost of extraction and therefore financial feasibility of acquiring the resource (Wessel Wentzel, [Deputy Director: NRM Regional Operations and Planning, Western Cape Environmental Programmes], personal communications, 8 July, 2016).

In terms of inventory of the available biomass, a marginal utility concept comes to mind; questioning how one should go about measuring such AIFs and at which stage does it become feasible to reject a particular inventory method in favour of another. Cost and in-field practicality will certainly feature as considerations in choosing an inventory method. Contractors could select a simplified method, checklist or decision-support system (DSS) over a complex forest inventory which can still reflect sufficient information necessary in creating a suite or variety of wood products from AIF sites (Pukkala & Kangas, 1993).

Eco-furniture and bioenergy enterprises can serve as end users of timber and biomass from invasive plant clearing operations. Such enterprises could contribute to economic development by making optimal use of timber and biomass, and in so doing create opportunities to manufacture products that help government to meet its needs, with a number of pro-poor opportunities. The long-term sustainability of these enterprises will however depend on the low-cost availability of suitable timber and biomass from clearing operations. Availability and use of biomass will depend on the product attributes required by eco-furniture and bioenergy enterprises as well as economically feasible transport distances (Mugido, et al., 2014).

Eco-furniture, for the purposes of this study, refers to furniture that has been manufactured by the VAI programme making use of materials (biomass) sourced from NRM clearing operations. The furniture ranges from school desks to more household items such as beds and tables. Other wood derived products the VAI programme produces includes kitchen cutting boards, coffins, decking, pallets, walking sticks, picture frames, plant boxes, shelving, and urns (Crouse, 2016).

The costs of the AIP clearing/harvesting programme have been borne by NRM through DEA, as well as land owners who have been willing to donate financially towards the programme. The income realised from clearing programmes was identified as a factor of the programme’s success, thus a need was recognised to try to extract an income from clearing programmes. The focus was to extract maximum value. One option was furniture for school desks (Wessel Wentzel, [Deputy Director: NRM Regional Operations and Planning, Western Cape Environmental Programmes], personal communications, 8 July, 2016).

1.3 Research objectives

This study has been undertaken to understand the potential for using AIF stands to source the raw material for higher-value products, including sawn boards for end-uses such as school furniture. The objectives of this study are:

1. To develop a system to classify different types of invasive stands per defined criteria of STPH and length of river bank occupied by AIPs.
2. To investigate in a representative case the standing volume available.
3. To assess the amount of utilisable sawlog volume available for enterprises from selected NRM clearing operations for the most suitable species and suitable product options.
4. To understand the sawn product volume (m^3) recovery possible from the AIF site this study is concerned with for defined product options (school desk boards).

The study considered various methods to assess utilisable above-ground biomass, through conventionally accepted plantation forestry and/or indigenous forest enumeration techniques, and new and unconventional enumeration techniques making use of cutting-edge technology. The current *status quo* method used by NRM was investigated and compared.

1.4 Expected contribution to the NRM programme

Many ecosystems, especially when sparsely invaded or even densely invaded for a short time, can recover after clearing without further management intervention, but others cannot (van Wilgen & Richardson, 2004). It is anticipated that the outcomes of this study will aid in the Management Unit Clearing Plan (MUCP) that NRM has designed to assist landowners in assessing the extent of clearing operations required to rid their land of invasive plant species permanently. This study will deliver estimates of utilisable standing volume which will aid the MUCP in scheduling clearing operations through income expected from the clearing (if any). The MUCP software can isolate land, schedule successive clearing operations for that piece of land (project), while taking the cost of the clearing into account and offsetting the cost against potential income from wholesale buyers (VAI programme). Figure 1 below is an extract from the MUCP software illustrating the different budget possibilities and their associated results in the form of average invasion density reduction over time.

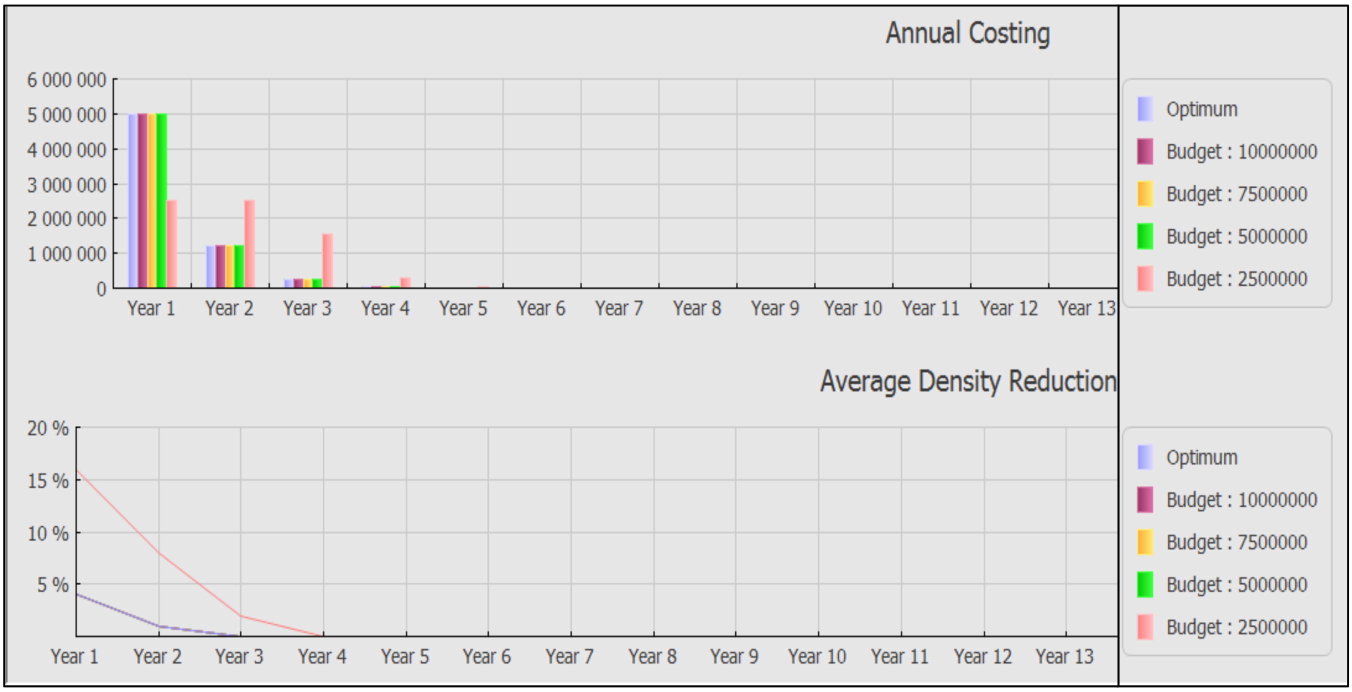


Figure 1: Extract from MUCP software for an exemplary invasive site. Top: annual cost of the clearing operations for each successive year. Bottom: results of budget input in average density reduction. Some of the budget options are not visualised in the average density graph as some of the lower budget inputs would be completely ineffective.

To extrapolate further and present another example of how the MUCP can be populated with information about invasion extent and density, Figure 2 and Figure 3 below show the invasion density of the broader Berg River study site increasing from 1997 to 2014. Images of this sort can be obtained from the Landsat programme and were compiled for the study site to visualise the extent of the invasive problem (Benfer, 2017).

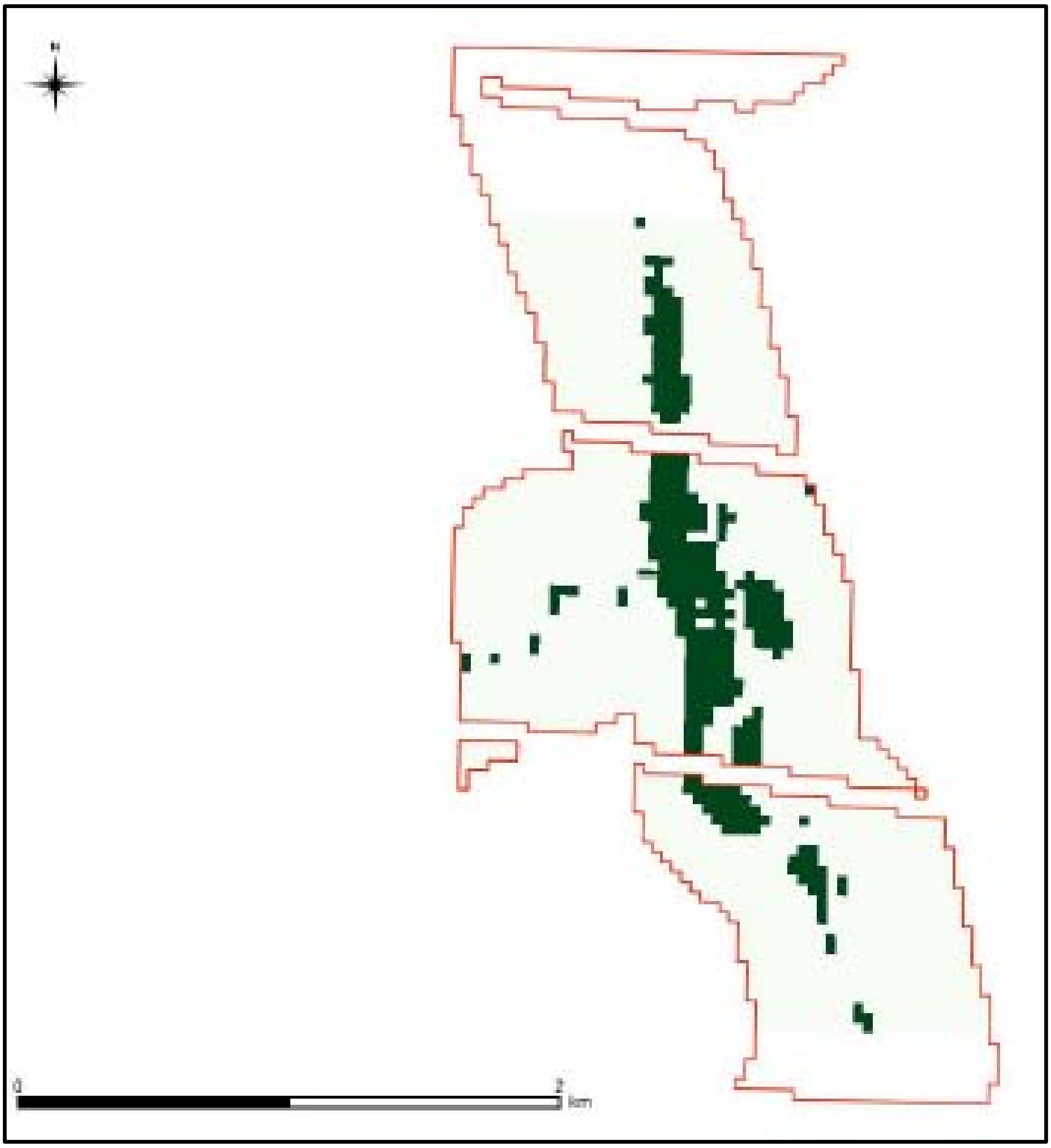


Figure 2: Landsat satellite imagery of the broader Berg River study site – 1997 (Benfer, 2017)

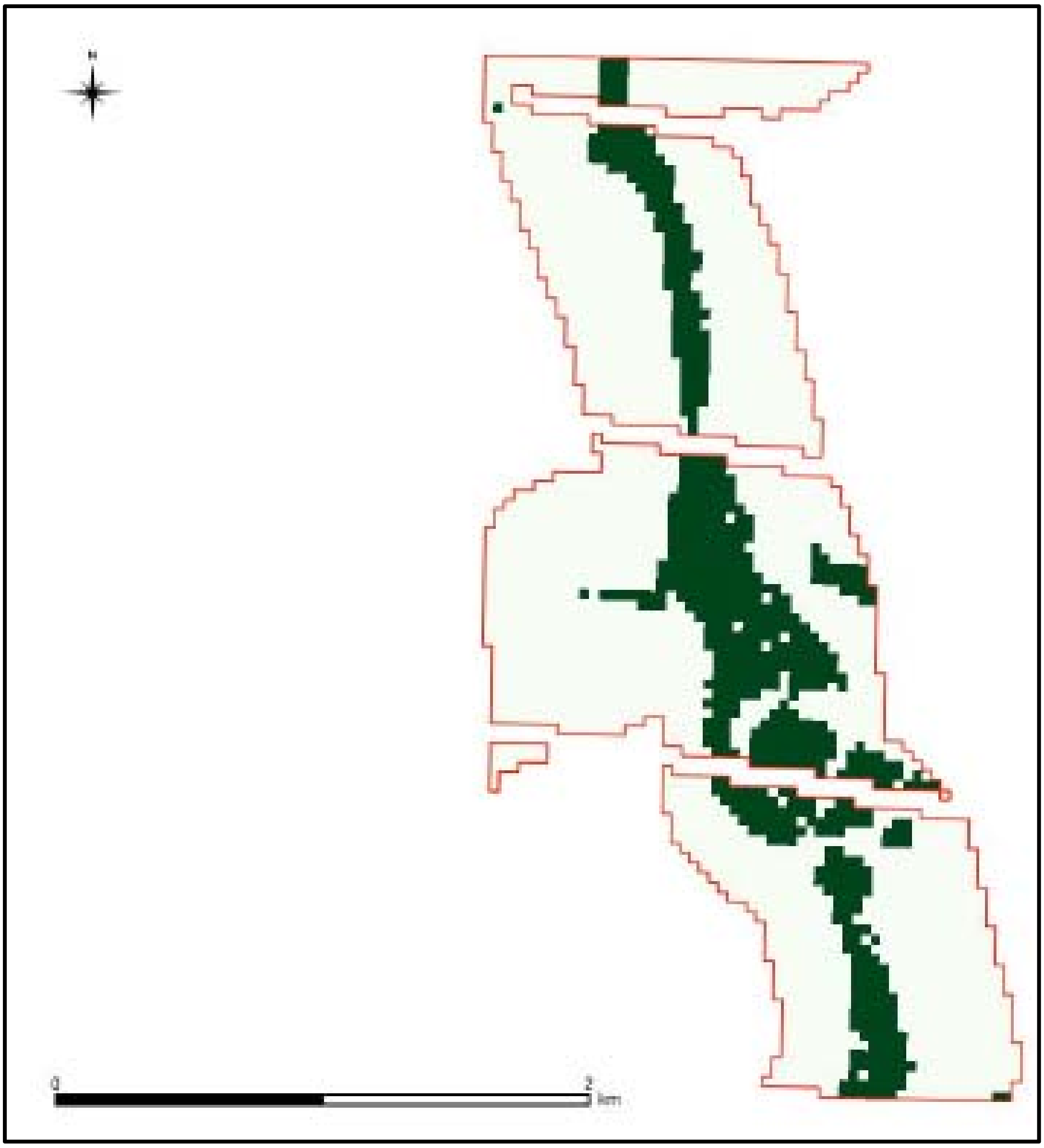


Figure 3: Landsat satellite imagery of the broader Berg River study site – 2014 (Benfer, 2017)

Chapter 2: Literature review

2.1 AIP species in South Africa

The following three sections deals with AIPs in South Africa. Literature pertaining to previous and current research initiatives on the topic is presented as well as findings of research investigating their distribution and density and the effects of AIPs on ecosystem goods and services.

2.1.1 AIP species research in South Africa

The area afforested with *Pinus* and *Eucalyptus* species in the southern hemisphere increased dramatically during the second half of the twentieth century (Richardson, 1998). *Pinus* and *Eucalyptus* species are the most common foreign species used in commercial forestry operations in South Africa with Australian *Acacia* species also prevalent (Godsmark, 2017). When foreign plants are introduced to an environment, a process of naturalisation takes place. Trees will regenerate freely, but mainly under their own canopies. Some however, will regenerate much further away from parent plants and thereby pose a threat to ecosystems. These AIPs will grow well on unsheltered bare land, produce desired wood products and show suitable physiological adaptation to take advantage of new environments and favourable growing conditions and periods (Richardson, 1998).

Research on AIP species introduced to South Africa was initiated in the 1930s, giving rise to multiple programmes over various allocated time periods, some still ongoing today. Table 1 below lists the research programmes on alien plant invasions in South Africa, past and present.

Table 1: Main research initiatives on alien plant invasions in South Africa (van Wilgen & Richardson, 2004)

Research programmes	Organisation(s)	Duration	Examples of important scientific outputs
Biological control of invasive alien plants	Department of Agriculture; Plant Protection Research Institute, Agricultural Research Council, Universities of Cape Town and Rhodes	1930 – ongoing	Synthesis volumes
Catchment conservation research programme	South African Forestry Research Institute	1973 – 1990	Detailed studies on key invaders and invasion processes.

South African National Programme for Ecosystem Research	Council for Scientific and Industrial Research	1977 – 1985	Regional syntheses
Scientific Committee on Problems of the Environment (SCOPE), programme on biological invasions	CSIR and many participatory organizations	1982 – 1986	Synthesis volumes
South African Plant Invaders Atlas	Plant Protection Research Institute, Agricultural Research Council	1975 – ongoing	Handbook and detailed distribution studies
Invasive plant ecology programme	Institute for Plant Conservation, University of Cape Town	1994 – ongoing	Synthesis volumes, conceptual contributions and application to management of invasions in the Cape Floristic Region
Working for Water programme	Department of Environmental Affairs	1996 – ongoing	First countrywide assessment of extent of woody plant invasions, Best management practices proceedings.

2.1.2 Distribution and density of AIP species in South Africa

The South African Plant Invasion Atlas (SAPIA), one of the broadest databases on AIPs in Southern Africa (Agricultural Research Council, 2014), identified approximately 180 species, mainly woody invaders that affect water resources (Figure 4 below). The greatest number of species recorded was in the Western Cape – along the eastern seaboard and into the eastern interior. Of South Africa's eight terrestrial biomes, fynbos (endemic to the Western Cape Province) is the most studied and the most invaded with dense invasions occurring in the mountains and lowlands and along all major river courses. The major invaders here are trees and shrubs in the genera *Acacia, Hakea*, and *Pinus* (van Wilgen & Richardson, 2004).

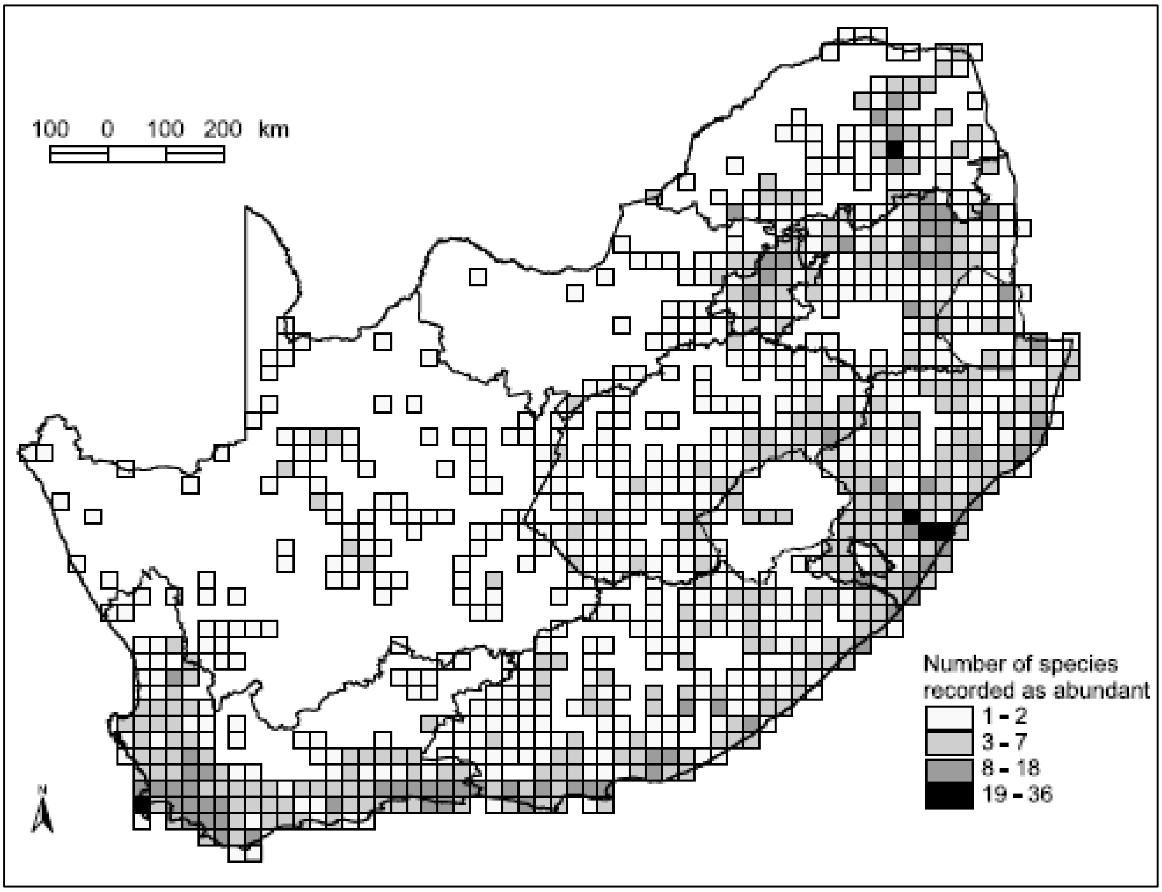


Figure 4: The distribution of AIP species in South Africa. Shading indicates the number of species listed as 'abundant' in each quarter degree cell (van Wilgen & Richardson, 2004)

Figure 5 below is taken from a survey report showing the extent (density) of invasions of foreign plant species throughout South Africa, emphasising sensitive riparian and catchment areas (Kotze, et al., 2010). From Figure 5, regions with high invasion densities can be seen to correlate with Figure 4 (above) where the same regions also have the highest number of AIP species recorded. The Western Cape (bottom-most left province) is an example of one such region, where dense invasions together with high AIP species diversity is found.

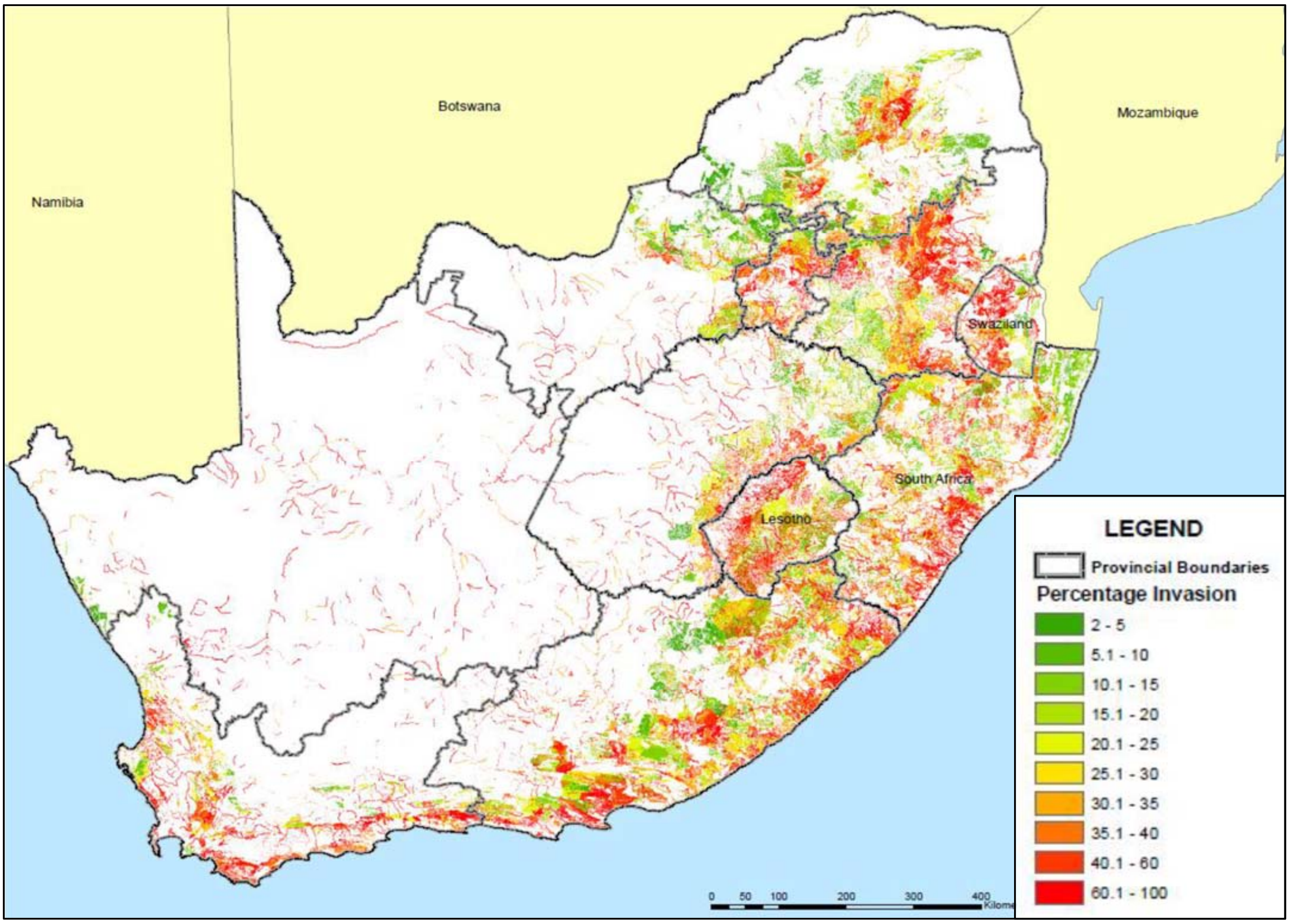


Figure 5: National AIP Survey map (Kotze, et al., 2010)

2.1.3 Effects of AIP on ecosystem goods and services

AIPs transform ecosystems using available resources, obvious examples being light, water and oxygen. These plants then add resources (e.g. nitrogen), while suppressing or promoting fire. Other means include stabilizing sand movement and/or promoting erosion, and by accumulating litter or by accumulating or redistributing salt (Richardson, et al., 2000). These changes alter the availability, flow, or quality of nutrient resources in biogeochemical cycles. They change trophic resources within food webs and alter physical resources such as living space, sediment, light penetration and water availability (Vitousek, 1990). Through altering disturbance regimes, they act as drivers of ecosystem engineering, consequently affecting ecosystem structure, composition and processes (Brooks, et al., 2004).

Most ecological research linking the effects of AIPs and ecosystem goods and services in South Africa has been conducted in the fynbos biome (Holmes & Richardson, 1999). Some direct effects in the form of reduced streamflow present clear consequences to water catchments and their ability to capture and store water while steadily releasing this water throughout the year (van Wilgen & Richardson, 2004). Increases in biomass resulting from reduced streamflow create greater fuel loads leading to a heightened fire hazard and risk of soil erosion (van Wilgen & Scott, 2001).

AIP species are generally considered to use more water, all things being equal, compared with similar native species. Other characteristics of AIPs include (Le Maitre, et al., 2015):

- The capability of some invaders to form stands denser than those of native species.
- Rooting depth of the invader species which allows them to access water at depths deeper than that of native species.
- The efficiency with which the invading species can produce woody tissues.

Generally, AIPs use more water than grasses or shrubs that they replace (Bosch & Hewlett, 1982), but this is due to the improved water use-efficiency of AIP species (Wise, et al., 2011). Introduced forestry tree species are more efficient at using water to produce harvestable biomass than indigenous species (Wise, et al., 2011). In semi-arid areas, water is the limiting reagent to biomass growth while in humid areas, temperature (low) or soil condition (e.g. high leaching) limits biomass growth. Using 94 catchment experiments, Bosch and Hewlett (1982) pointed out the effect of afforestation on streamflow. Replacing a low canopy vegetation (e.g. fynbos in the Western Cape), with a denser and taller vegetation reduces streamflow. These reductions in streamflow during periods of low rainfall place further stress on riverine ecology and available water for agriculture, for example. In some cases, replacing natural grassland or indigenous brushwood with pines and eucalypts causes streams to completely dry up (Enright, 2000).

The negative effect of AIPs on South Africa's water supply is heightened during periods of drought. Communities as well as agricultural operations with little or zero water storage capability depending on free-flowing water are put at risk of experiencing decreased yields and water shortages (Enright, 2000). Ecosystem goods and services have been subsequently compromised by the introduction of AIP species (van Wilgen & Richardson, 2004).

A study carried out on three sites in the Western Cape Province of South Africa found that there is indeed a benefit associated to clearing unwanted invasive trees in terms of water production (Prinsloo & Scott, 1999). Improvements to streamflow were noted after alien invasive tree species (*Acacia mearnsii*, *Hakea sericea*, *Acacia longifolia*, *Pinus pinaster*) were cleared from an area of about 37 m on either side of a stream. The responses to clearing and subsequent streamflow improvements were however deemed maximum since the studied areas require a vegetation cover causing the streamflow increases to taper off and stabilise. Indigenous vegetation, such as grass or fynbos, should replace the cleared invasive vegetation to sustain the long-term increases in streamflow (Prinsloo & Scott, 1999).

2.2 Forest inventory and stem form

The following four sections deals with literature pertaining to the history of forest inventory, inventory of AIP stands, and the optimisation of such inventories. Stem form is also investigated with progress and improvements in the various devices and technology used in measurements of stem form covered.

2.2.1 Forest inventory and the situation in invasive stands

The first forest inventories were carried out in Europe in the 14th and 15th centuries (Tomppo, et al., 2010). Mining activities saw the depletion of the forest resource creating the need to improve its longevity. By the 19th century forest inventory was a recognised component of forest management (Kleinn, 2013), but based mainly on visual assessment (Kangas, et al., 2006). The first large area inventories took place in Sweden in the 1840s and the first in the tropics in Burma in the 1860s. With the development of statistical sampling theory (post 1900), progresses in forest inventory were driven by advancements in statistics (sampling and modelling), remote sensing (aerial and satellite imagery), computing, measurement devices, road infrastructure (increased accessibility to remote areas), and means of transportation (Kleinn, 2013).

In managed forests, inventory is an essential tool for making decisions and planning around resource harvest and renewal. Forest inventory can occur at a local (regional or geographical), national, and international level (Tomppo, et al., 2010). Typically, these different levels of inventory require data to satisfy different needs – e.g. local inventory for operations of forest enterprises (planning, management, harvest, silviculture), national inventory for policy and reporting (climate change, sustainability, biodiversity, forest health), and international inventory for international collaboration towards achieving agreements such as Reducing Emissions from Deforestation and Forest Degradation in developing countries (REDD+) (Asrat & Tesfaye, 2013).

A forest inventory could measure every tree (complete census) or a sample of trees (proportion of the population). To measure every tree in a forest is nearly impossible due to the large area extent and high number of trees, therefore measuring a sample of trees with which inferences about the population could be made is the acceptable practice (Kangas, et al., 2006). But while this is done routinely in managed forests, the situation in AIP stands is different. The VAI programme has utilised the resource, but only now has the need to measure the resource specifically for utilisable sawlogs been realised.

Extensive research has already been conducted AIPs in South Africa (Table 1). Numerous studies concerned with modelling of available biomass in invaded areas in the Western Cape have been carried out (van Laar & Theron, 2004; van Laar & Theron, 2004; Le Maitre, et al., 1996). Other studies pointing out the feasibility of bioenergy production from NRM clearing operations have been conducted on the backbone of these biomass models (Mugido, et al., 2014). These studies present models (based on predictor variables) for an AIP site's utilisable biomass which could, for example, be chipped and transported to bioenergy facilities near-by. They, however, do not provide meaningful insight into characterising stem form, and by extension stem quality, particularly for tall, large trees. The approach of a biomass study is to define as much of the entire tree's above-ground biomass (foliage, branches, and stem) (Juba, et al., 2017), but does not necessarily define timber from a commercial sawmilling perspective.

A recent study by Stafford and Blignaut (2017), investigated the feasibility of using AIP biomass for the generation of electricity on the Agulhas Plain (different region to the study site, but still within the Western Cape Province). The study classified the quantity and suitability of AIP biomass for the region. Biomass suitable for lumber constitutes the least of the resource while biomass suitable for electricity (bioenergy) and fuel woods constitutes the most (Figure 6). This is based on remotely sensed aerial data (scaled rectified orthophotography) of the study site (100 m x 100m resolution) classifying biomass and the availability thereof in a techno-economic feasibility study.

Slope, proximity to riparian area, distance from clearing area to roadside, distance from roadside to processing plant, and biomass yield were used to classify biomass availability for the region (Mugido, et al., 2014). Only a third of the total biomass was classified as available once the classification criteria were factored in (Figure 6).

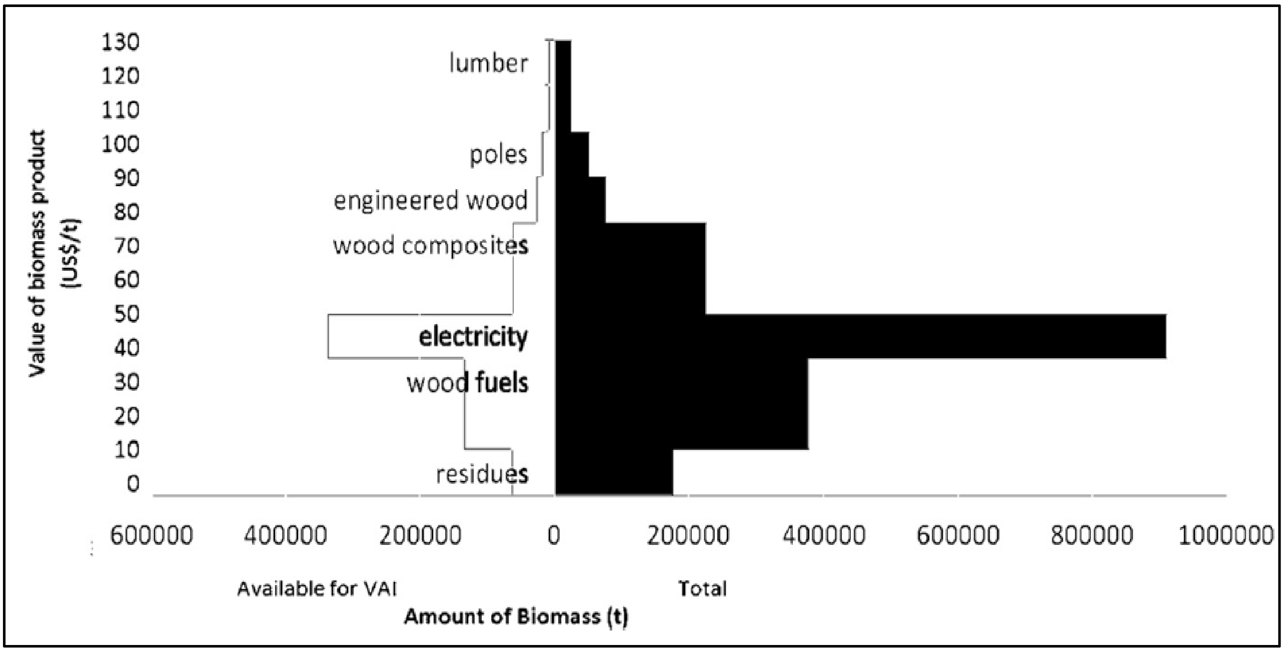


Figure 6: A value versus volume pyramid for value-adding opportunities from woody IAP biomass on the Agulhas Plain. y-axis: Market value of the biomass product per tonne (US$/t). x-axis: Amount of biomass (t) with right-side showing the total biomass and the left-side showing biomass accessible and available for value-added industries. Biomass amounts are oven-dry tonnes (t) (Stafford & Blignaut, 2017)

AIP stands resemble forests and woodlands; wooded areas with greater than 10% canopy cover, where the canopy is comprised of mainly woody plants that are self-supporting, single-stemmed, or a few definitive trunks branching above ground level, and greater than 5 m in height (FAO, 2000). This means that conventional indigenous and plantation forestry enumeration techniques can be applied to AIP inventories.

Angle Count Sampling (ACS) is a method of determining stand volume with a simple formula using basal area (BA) per hectare and mean stand height. The method was developed by an Austrian forester (Dr W. Bitterlich) in the 1930s and uses a method of counting the number of trees in a 360˚ sweep that at breast height appear to be larger than an angle gauge with a known BA factor. An angle gauge is a piece of wood, metal or plastic with a specified width which is held a specified distance from the eye. Deciding on the correct size angle gauge to use is dependent on the number of trees deemed as ʻʻinʼʼ trees. Ideally, standing in one position and doing a 360˚ sweep should yield on average between 5 and 10 trees. Once an adequate angle gauge is decided on, trees can be counted, average BA per hectare can be estimated (at multiple locations throughout the stand using the 360˚ sweep method), and standing volume can be calculated by multiplying BA per hectare by mean stand height and a species-specific form factor (Kassier, 2011).

Total biomass and the subsequent ecological effects of AIP introductions are the topics of main concern for AIP studies in South Africa (Juba, et al., 2017; Wise, et al., 2011; Gorgens & van Wilgen, 2004). In biomass estimation it is not uncommon to use conventionally accepted standing volume equations as a substitute for calculating biomass by using measurable tree characteristics (DBH, total tree height) as predictor values (Husch, et al., 1982). The calculated biomass values are then compared to the biomass of a sufficient sample of felled trees on the same target site to gain an adjusted tree-level model (Theron, et al., 2004). Upscaling to stand and then regional level is done by comparing calculated biomass on plots of several sizes (per unit area value – usually hectare) and then by using satellite imagery to estimate infested area (Theron, et al., 2004). This study aims to quantify available utilisable sawlog volume (biomass), non-destructively, while also measuring stem form (quality) related to the volume.

2.2.2 Analysis and optimisation of a forest inventory

Sample design and plot design are of considerable importance in forest inventory. The optimization of these in an inventory requires both statistical and practical considerations. Due to the high-costs of field data collection, practical considerations such as plot measurement time and travel time between two neighbouring plots can play a significant role in the chosen sampling design (Zeide, 1980). While measurement and travel time were initially not major considerations in this study, these factors were taken into consideration in an optimization of the inventory. "The optimal plot size is that which minimizes total time for location and measurement for a stated accuracy in the desired variable (usually volume). Thus, the problem is (1) to express total time as a function of plot size and (2) to find the plot size which corresponds to the minimum of this function" (Zeide, 1980).

In order to define a desired number of plots as a function of plot size; accuracy, precision (through the use of standard error of the mean), coefficient of variation between plots of the same size and an appropriate Student's *t*-statistic value are used in an iterative equation, suitable for use in a pilot study. The pilot study is tasked with capturing data about a particular variable and then iteratively testing the number of observations required to reach a desired level of precision (van Laar & Akcha, 2007).

Use of stratification to reduce variability in the measured resource is a statistical technique applicable to this study. Sometimes for practical, organizational, or administrational reasons it is useful to subdivide the population into subpopulations. If there is an interest in optimising the statistical precision of the inventory, the subpopulations (strata) must be defined according to specific characteristics of these subpopulations (e.g. in terms of species or species group). The most efficient gain in precision comes when the mean values of a target variable differ as much as possible between strata (van Laar & Akcha, 2007).

Species stratification and stratification according to potential for merchantable lumber is of interest to this study. For example, to state that below a minimum processable DBH, no trees shall be measured. This will allow the inventory to be optimized to deliver reporting specifically for utilization of the resource by the VAI programme.

Stratification can be carried out before, during, or after an inventory. If much is already known about the resource (e.g. inventory of a plantation compartment with prior inventories logged), little effort is required to define sampling frames for the strata. Whereas, inventories where little (or nothing) is known about the resource prior to sampling, techniques can be applied to form strata after field data is collected. Strata can be formed during the field data collection process, for example, by a sampling technique such as double sampling for stratification (DSS) which is used when it is not possible to define strata clearly before sampling. Double sampling consists of two phases, first a large sample is taken in order to gauge the relative size of the strata needed (e.g. DBH measured to understand the site's frequency distribution), then a stratified sub-sample is taken from this first sample (e.g. to rather sample trees with DBH larger than the mean DBH as these are more suitable for processing in a sawmill). This second phase of sampling can be dependent on the first (i.e. resampled from the first sample population) or independent of the first (i.e. sampled from a different population to the first) (van Laar & Akcha, 2007).

2.2.3 Stem form and taper functions (empirical)

The term "form'' used by forestry practitioners is a broad term used to describe directly or indirectly a variety of factors or conditions leading to the recovery of good-quality timber from a standing tree. Poor stem form is used broadly to describe trees with lean, bumpy stems, heavy/low stem branching, abnormally rough barking, forked trees, as well as trees left with an asymmetrical form owing to damage from exposure to events or periods of drought, storms, frost, fire, sun scorch/leaf scorch, animals, insects, disease or fungi (Gray, 1956). Good form in a tree can be summarised as straightness of stem, minimal branching, symmetry, and damage-free. Form has also been used to describe the relative shape of the tree (Burkhart & Tome, 2012). It's important to note that form describes tree condition, not only stem straightness (Gray, 1956) and for this study the characterisation of stem form will play an important role in achieving the stated objectives.

For a tree stem, taper can be defined as a decrease in stem diameter with an increase in height/length (Bredenkamp, 2012). Two of the most prominent theories developed to explain the varying manners by which trees grow woody biomass (and therefore how they taper) are the Hormonal theory (Larson, 1963) and the Mechanistic theory (Metzger, 1893). The underlying assumption states that tree growth and stem form development follows inherited designs, but these can be adjusted through silvicultural and environmental factors (Larson, 1963). For example, with stem shape remaining constant, responses to thinning (silvicultural regime) will cause a strong increase in taper of remaining trees when compared to trees in unthinned stands (Karlsson, 2000).

Mechanistic theory suggests that if a tree was anchored firmly to the ground it would take on the form of a column of uniform resistance to bending, allowing for a constant uniform taper, approximated to a truncated cubic paraboloid shape (true at least for coniferous species) (Larson, 1963). Others have suggested it is rather a truncated quadratic paraboloid (Gray, 1956); horizontal wind forces being the main environmental factor influencing changes to tree form (e.g. causing lean).

Hormonal theory provides a physiological explanation to tree form by suggesting substances in the cambial layer of the tree crown influences lateral woody growth, but cannot provide reasons for tree shape under varying circumstances (Brack, 1997).

Taper functions have been studied intensely for the last 40 years (Gomat, et al., 2011) and with taper influencing stem form and trees not growing perfectly cylindrical stems, taper functions have been developed which describe different sections of the stem as geometric frustums (Figure 7). These are variations ranging between a perfect cylinder and cone, but still represent a geometric solid. The neiloid frustum shape can be used to define the taper of the lower/butt section of a tree, paraboloid frustum the section of stem between butt and crown, and cone the crown (Max & Burkhart, 1976). Different taper equations have been developed and tested for forest trees. Key innovations include polynomial (Demaerschalk, 1971), trigonometric (Thomas & Parresol, 1991), variable form exponent (Ormerod, 1973), and switching bole taper equations (Valentine & Gregoire, 2001). Equations such as the Max and Burkhart (1976) segmented polynomial function join these different sections of the bole together at inflection/graft points to describe the stem profile.

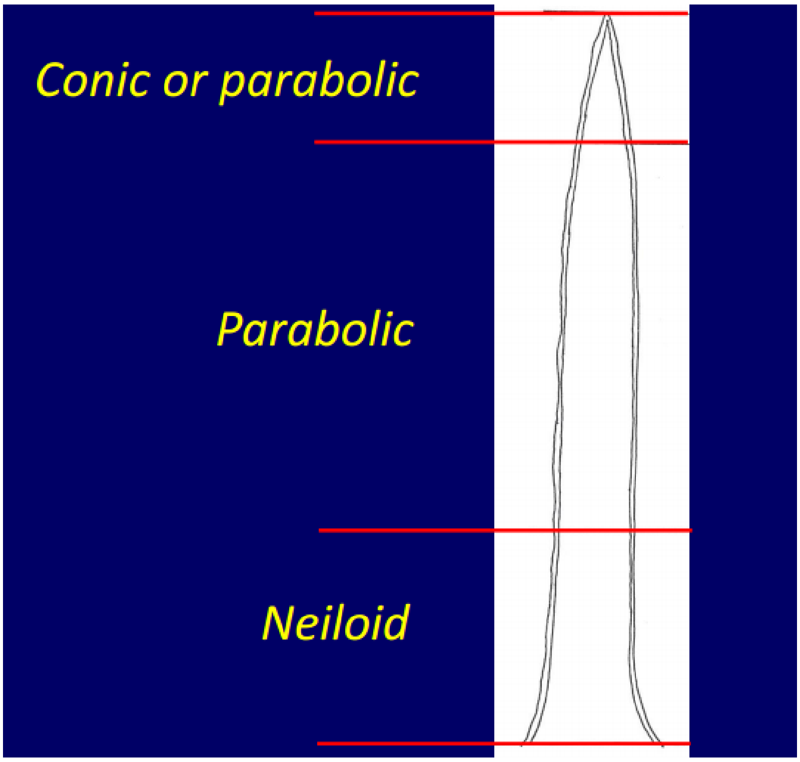


Figure 7: Diagram showing combination of three different geometric frustums used to describe stem shape

Furthermore, the greatest degree of taper is found in the crown of a tree owing to the increase of branches and growth contribution of branches (supporting needles/leaves responsible for photosynthesis) to lateral stem growth (Brack, 1997).

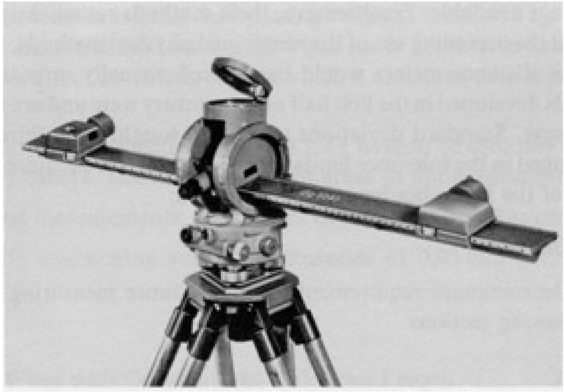
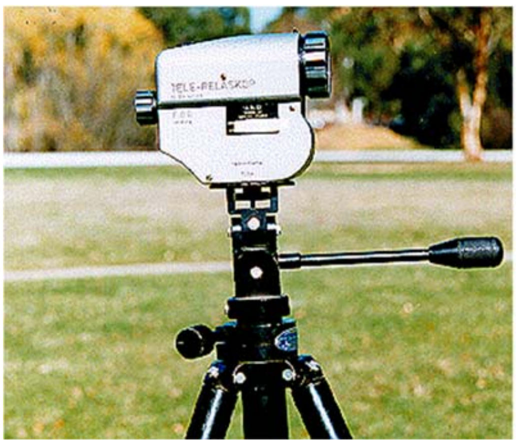
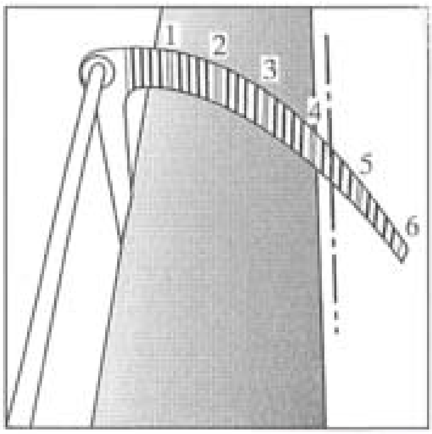
2.2.4 Measuring stem form

(a) Dendrometers

Instruments collectively classified as dendrometers are used to measure stem (upper) diameter on contact or non-contact (remotely) (Nash, 1973). Dendrometers can be further classified as optical forks, optical callipers, fixed-base range finders and fixed-base angle finders. Some examples of dendrometers include instruments such as the Spiegel Relaskop, Barr and Stroud, Optical Wheeler Pentaprism, Criterion device, Tele-relaskop, Breithaupt Todis dendrometer, Finnish Calliper/Bitterlich Sector Fork and Gator Eyes laser calliper (Table 2). Some of these devices can measure height together with diameter. Dendrometers have been used for nearly 100 years (Weaver, et al., 2015), some are therefore more sophisticated than others, delivering improved usability in rugged conditions over earlier versions (Nash, 1973).

Further differences distinguish analogue from digital dendrometers, but what these instruments have in common is that they can take measurements non-destructively (some from a distance, others on-contact) (Weaver, et al., 2015). Ideally, dendrometers need to be easy to use, inexpensive, and free of bias (Kalliovirta, et al., 2005). Accuracy of laser dendrometers depends on tree diameter, distance from tree (or measurement point), and measurement time (Skovsgaard, et al., 1998).

Table 2: Examples of various dendrometers, old and new

 Barr and Stroud (Carr, 2004)	 Breithaupt Todis (Wrona, 2017)
 Criterion RD 1000 (Forestry Suppliers, 2017)	 Spiegel Relascope (Bitterlich, 1984)
 Tele-relascope (Brack, 1999)	 Finnish Calliper/Sector Fork (Keller, 2005)

 Gator Eyes Laser Calliper (Haglöf Company Group, 2017)	 Wheeler Pentaprism (Forestry Suppliers, 2017)

A point of concern is the accuracy of the upper stem diameter measurements using specifically the gator eyes laser calliper. A study carried out in the southern United States across three different forest types (older deciduous, older coniferous forest, young coniferous) found that the tested laser calliper delivered accurate ($p < 0.05$) DBH measurements within 12 m from the tree when compared to measurements taken with a diameter tape (Weaver, et al., 2015). The average deviation of the laser calliper to the diameter tape across all three forest types was 0.55 cm or less. When considering distances (3 m, 6 m, 9m, 12 m) to the subject tree, this accounted for 2% or less of deviation. The study also concluded that the laser calliper was effective at measuring diameters remotely across forest types. The measuring scale used for distance measurements on the laser calliper is given in 0.5 cm intervals whereas the scale for contact measurements is given in 0.1 cm intervals. Some accuracy is lost when taking measurements from a distance, but only if the measurement is deemed to fall within the 0.5 cm intervals.

(b) Remote-sensing

Remote-sensing techniques obtain information about an object, area or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation (Lillesand, et al., 2015). Remotely sensed data can take on many forms, for example, force distributions, electromagnetic distributions, or acoustic distributions (Lillesand, et al., 2015).

Other more sophisticated systems can be used to digitally characterise tree stem form such as LiDAR and photogrammetry. LiDAR (Light Detection and Ranging) is a versatile 3-dimensional imaging system; the laser/light equivalent of radar. LiDAR transmits optical light in pulses to determine distances to objects by recording phase differences or by calculating the time it takes to receive a return pulse once reflected off an object. Through a high rate of pulse emission and return, detailed images of scanned objects can be produced. LiDAR systems can deliver raw point returns (3D point cloud) or contours and surfaces used for topographic purposes (digital elevation models) compatible with geographical information systems (GIS). Today LiDAR systems can be utilised over terrestrial (stationary or mobile) and aerial (manned or unmanned aerial vehicle) applications (Jain & Favorskaya, 2017).

Terrestrial laser scanning (TLS) can be used for accurate, repeatable, and highly detailed documentation and measurements of forested environments (Thies, et al., 2004). Multi-scan TLS is used to collect plot-level tree data so that all stems can be detected and analysed (Liu, et al., 2017). Today, systems have been developed which can automatically register multiple laser scans to one another (Liu, et al., 2017) as well as detect tree stems and extract tree-level data (diameter, lean, sweep) from these stems (Kelbe, et al., 2013). Combining aerial and terrestrial laser scanning is also an effective tool to characterise stem attributes (Lindberg, et al., 2012).

A useful method for extracting stem diameter from incomplete remotely-sensed point cloud data is the least squares method of circle fitting. The least squares fit (LSF) is based on minimising the mean square distance of the fitted curve (circle) to data points along an otherwise incomplete curve (circle) (Chernov & Lesort, 2005).

Photogrammetry uses photographs as input to mapping and surveying to obtain measurements of/between objects. It can be defined as the “science of measuring in photos’’ (Linder, 2003). It has proven to be useful in the characterisation of tree stem form and the extraction of tree-level parameters (DBH), but with some drawbacks in that image-based point cloud data limits the mapping of small trees and complex forested environments (Liang, et al., 2014).

(c) Stem sweep

Log sweep is defined as the maximum deviation of the stem centre line from a chord (Thies, et al., 2004). A study conducted in 2004, used a similar system of defining log sweep from terrestrial LiDAR (Light Detection and Ranging) point cloud data. This was done by fitting successive cylinders to reconstructed stem sections with the centre axis line of the fitted cylinders constituting the circle’s arc (Asikainen & Panhelainen, 1970). The circle’s chord is defined as the centre line connecting the lowest centre point of the first cylinder to the top most point of the highest (last) cylinder (Figure 8). Numerous chords can be defined, e.g. by creating linking lines between various fitted cylinder centre points.

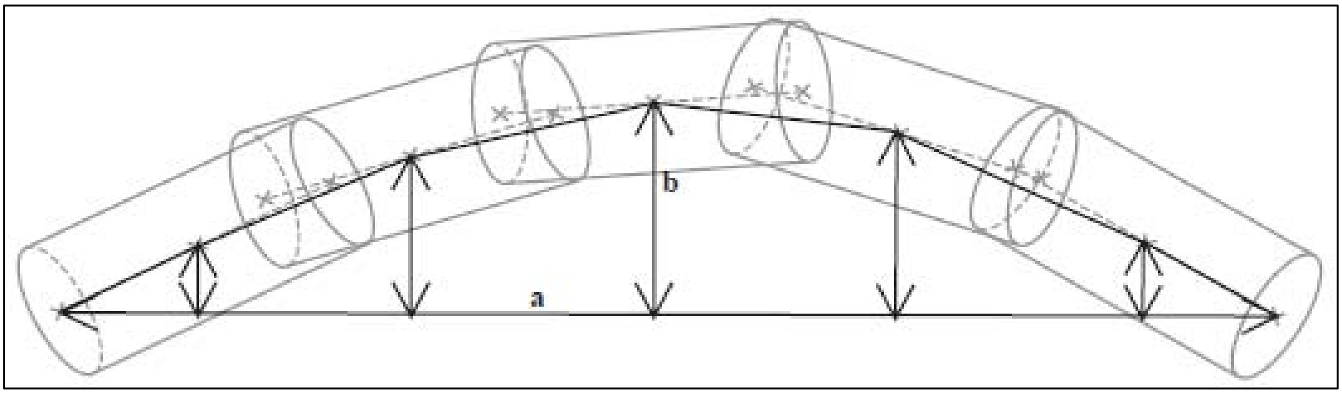


Figure 8: Fitted cylinders with centre points, approximated tree centre line (connections of fitted cylinders centre lines), chord (a) over whole stem length, and maximum corresponding deviation (b) of stem (arc) from chord (Asikainen & Panhelainen, 1970)

(d) Visual Stem Form Assessment

Tree grading systems like MARVL (Methods of Assessment of Recoverable Volume by Log Types), used operationally by the New Zealand Forest Service, now replaced by a revised version called Cruiser (Gordon & Pilaar, 2008), which uses a grading system to estimate tree and therefore log quality by assessing the effect of stem quality, malformation, log specifications and user/buyer preferences (Deadman & Goulding, 1979). Log quality is used to refer to the presence or absence of defects which in turn affects what the log could be used for; pulpwood, sawlogs, or better (e.g. veneer wood). The system requires an inventory measuring upper stem diameter and height, and total tree height. In this way, a tree can be divided into different logs of varying quality based on size, length and defects. The system can also be used in a product yield assessment without recording any quality or malformation information, making use of only log dimensions and log values (Deadman & Goulding, 1979).

The gator eyes laser calliper is a tool that can be employed within the MARVL-inspired system to estimate utilisable sawlog volumes through measurements of upper stem diameter. Although the MARVL system (Deadman & Goulding, 1979) was developed for use in plantation compartments comprising of even-age and single species trees, there is potential to use this system in the multiple species invasive forests this study is concerned with.

Similar systems of visual tree grading exist and are used in the USA (McAlister & Clark, 1998). A visual tree grading system for *Pinus* was developed with the cooperation of state and federal agencies and industry. This system differentiates between two age classes, young (<35 years) and mature (≥35 years) and grades trees according to the number and size of branches in the lower bole (live and dead), allowable sweep (minimum 2.43 m up the stem) and the presence of seams and cankers, and decay and rot. Three grades/categories are defined; grades 1, 2, and 3, with an expected lumber yield for each. Sawlog value for grade 1 trees is higher than grade 2 trees, and grade 2 higher than grade 3, for both mature and young trees. Tree form/condition is assessed and sawlog value estimated (according to tree grade, dimensions, age) using a regression function developed from lumber grading results after subsequent sawmill processing (McAlister & Clark, 1998). This system shows potential to be used (with some adaptions) in AIP stands. Because age is not clearly discernible in AIP stands, tree dimensions could be used exclusively (e.g. only measure trees above a defined threshold diameter).

Two distinct categories of timber quality classification exist, namely; absolute grades (dimension grades), and relative grades. Quality is based on discrete variables expressed on an ordinal scale. Absolute grades are based on tree dimensions (e.g. minimum bottom or top diameter and length), whereas relative grades are based on the most valuable product attainable from a stem (Köhl, et al., 2006).

Recoverable sawlogs have been investigated in harvesting practices, but rather to assess systems productivity. Relatable to forest inventory, cut-to-length versus whole-tree harvesting systems can provide insight into quantifying sawlog lengths. Mean DBH of 27.94 cm (11 in.) was measured over two sites with a cut-to-length harvesting system consistently sawing logs to lengths of 4.96 m (16.3 ft.) (Adebayo, et al., 2007). These lengths are applicable to mixed-species uneven aged stands in Canada (70 – 130 years), and reflect mean sawlog volume. A study carried out in Finland used a diameter-and-length (minimum) method of defining the proportion of sawlog in the stem; 15 cm and 3.7 m (pine), 16 cm and 3.1 m (spruce), and 18 and 3.3 m (deciduous species) (Korhonen, et al., 2008). If a tree could not deliver a log conforming to the dimensional requirements, it was not considered a sawlog.

(e) Form factor volume estimation

The form factor of a tree refers to a ratio defined by the volume of the tree compared to a geometric solid (most commonly cylinder) of similar basal diameter and height (Brack, 1997). Form factors deliver volume estimates meaning that diameter at breast height or at various positions up the stem must be measured. Because various reference positions up the stem can be measured, various form factors types have been developed (examples included); the absolute form factor (Claughton-Wallin & McVicker, 1920), the normal form factor (Kajihara, 1969), true form factor (Socha & Marian, 2005), and the breast height form factor (Inoue, 2006).

Stem form variation is of concern regarding precision and accuracy of tree volume estimation using form factors; this is due mainly to the differences in stem diameter growth rate at different stem heights (Mitscherlich, 1970). The use of the form quotient introduced a convenient method of measuring form factor (as opposed to destructive stem height and diameter measurements) and requires a diameter measurement at breast height and at a stipulated height above breast height.

Classes were developed to categorise tree shape according to the results of many form quotient measurements. Jonson (1928) developed tables defining stem profile and therefore form factor by using various form classes, dependent on diameters measured at a percentage of tree height, and as a percentage of DBH (van Laar & Akcha, 2007).

Chapter 3: Materials and Methods

3.1 Development of Sawlog Volume Correction Factor (SVCF) for invasive forests using sampled and sub-sampled tree data

A key objective in this study was to estimate the level of utilisable sawlog volume which could be expected from an unmanaged stand of trees with highly variable form with the intention of assessing sawn product recovery from the wood resource. Utilisable sawlog volume refers to the section of stem of a tree that can be processed by a sawmill. This stem section/log should comply with specifications of log quality set out by the relevant sawmill in accordance with the specifications of their respective manufactured wood products. Each company can set out different sawlog specifications, but generally sawlogs should be defect-free and straight (James, 2001).

This was estimated incrementally, taking the approach of incrementally adding increasing information from a "basic" start point. That is, if no information other than diameters at breast height and a subset of heights were available; the total standing volume of individual trees (Schumacher & Hall, 1933) could be estimated relying on models developed for the relevant species in commercial forest stands. This was the approach taken to dealing with the objectives of the study; to investigate in a representative case (i.e. "the study site" delineated in section 3.2), the standing volume available as well as assessing the utilisable sawlog volume available for enterprises from selected NRM clearing operations for the most suitable species and suitable product options.

With increasing information about tree taper and form, new information can be added to the "control" log volume to investigate what loss of sawlog volume resulted from, for example, actual expected taper and taper variability, or deviant form, or low branching. This is the approach that was taken, as shown in Figure 9, to create an incrementally updated "sawlog volume correction factor" (SVCF) towards defining potential losses in utilisable sawlog volume. These losses in sawlog volume will ultimately affect sawn product (Table 3) volume output. Figure 9 is a process-flow diagram illustrating how tree form data captured in the study treatments is used in creating the SVCF. In effect, the SVCF will compare the invasive wood resource to a conventionally managed plantation resource of the same species.

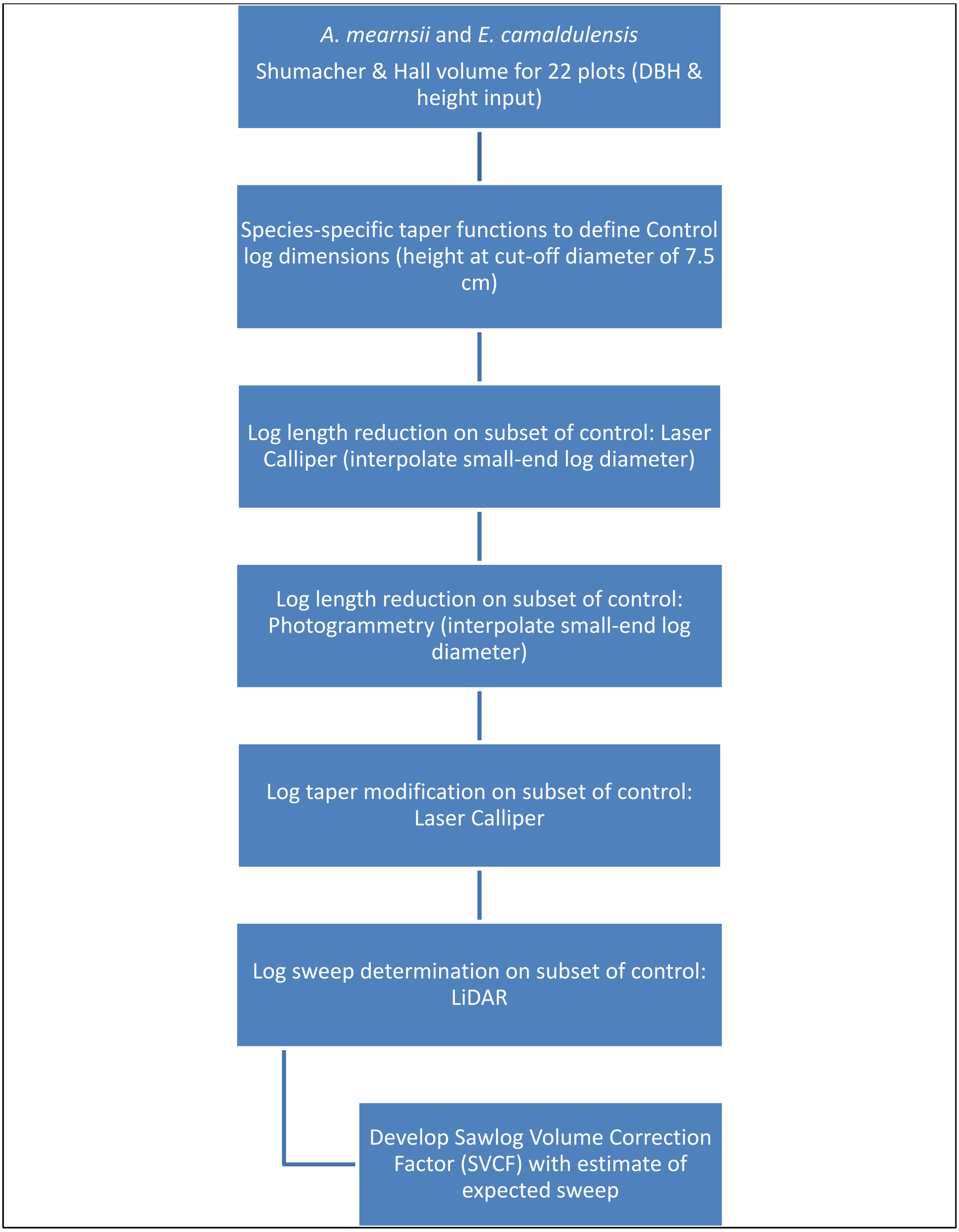


Figure 9: Flow diagram illustrating the use of treatment data (Control, Laser Calliper, LiDAR) in the creation of a sawlog volume correction factor (SVCF) towards a realistic estimate of utilisable sawlog volume for *Acacia mearnsii* and *E. camaldulensis* on the study site. Sweep causes no change in log volume; sweep estimate results will however be presented.

The creation of a SVCF for the studied forest depends on capturing sufficient data regarding tree form. Starting from a full 8.5% inventory, the more detailed measurements made on sub-samples of trees using laser callipers, photogrammetry, and LiDAR added data to be able to make further inference about actual variability in relevant variables. While sawn product volume recovery is tested, specifically to produce boards for school desks, due to practical concerns surrounding the reliability and reproducibility of a so called "board recovery correction factor'', the study will rather emphasise the losses in utilisable sawlog volume attained from AIFs. This incrementally reduced utilisable sawlog volume is intended for use in a sawmill environment to produce sawn timber products. The trouble with producing a correction factor based on sawmill board recovery is interaction of the variables affecting volume recovery and how this interaction can differ from one sawmill to the next. For example, dimensions of the log resource, sawmill machinery type and condition, and operators of the machinery can influence volume recovery (Steele, 1984).

Sawlog volume can be calculated in a basic sawmill simulation software like Simsaw 6 (CSIR, 2000). This software was used to create the SVCF, and as a side note, test subsequent recovery volume of sawn timber products (boards). In this study, sawn product volume recovery refers to the percentage of a log's volume which can be converted into boards of various widths and lengths for use in the manufacturing of school desks. It represents a theoretical measure of log utilisation in a sawmill (utilisation factor/percentage). More information on the Simsaw 6 software package is presented in section 3.2.

While the subject of sawn product volume recovery is important, many variables underpin it. Starting with the log itself (diameter, length, taper, grade) to the mix and variety in dimensions of desired output products (big boards for school desks to small off-cuts for knife handles) to the sawmill itself (sawing method, blade width, personnel decision-making). The variables influencing volume recovery are therefore numerous and interact with each other (Steele, 1984). This variable interaction is the reason for rather creating a ''sawlog volume correction factor'' over a "board recovery correction factor'' as it will give NRM personnel and harvesting contractors more insight into the standing utilisable sawlog volumes present on the study site which can be used to discount the price of harvesting and then be used for various timber-products at the contractor's/timber owner's discretion.

Before simulations testing sawn product volume recovery could be undertaken, the desired sawn products had to be defined as the volume recovery from sawing simulations is influenced (together with other variables mentioned above) by the dimensional variety of the respective sawn products. To this end, a standard of output products had to be decided on. The component boards listed below in Table 3 (Crouse, 2016) are used to manufacture school desks listed in Table 4 (Crouse, 2016). Primary and secondary used in Table 4 refers to the pupil the desk is intended for, primary for primary school and secondary for high school pupils. Double and single refers to how many pupils the desk can accommodate at one time; single, or sharing between two pupils. Higher and lower refers to the height of the desk.

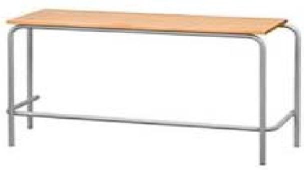
The products presented in Table 3 represent a particularly limited case for sawing options. In this way, confusion around the broad range of product options the VAI programme has at its disposal and the issues of optimisation associated with creating sawing simulations for those products is minimised. Creation and optimisation of sawing simulations is done manually in Simsaw 6.

Dimensions for wet and dry boards are presented. The wet dimensions for thickness and width are roughly 3.5% larger than dry dimensions. This is to account for product shrinkage from the drying process and allows for boards to be of the desired dimension once dry.

Table 3: List of component wooden boards used in the manufacturing of school desks by the VAI programme (Crouse, 2016)

Component board no.	Board dimensions (dry)	Board dimension (wet)
I	30 mm x 110 mm x 600 mm	31 mm x 113.8 mm x 600 mm
II	30 mm x 110 mm x 700 mm	31 mm x 113.8 mm x 700 mm
III	30 mm x 110 mm x 1100 mm	31 mm x 113.8 mm x 1100 mm
IV	30 mm x 110 mm x 1200 mm	31 mm x 113.8 mm x 1200 mm
V	30 mm x 110 mm x 1300 mm	31 mm x 113.8 mm x 1300 mm
VI	30 mm x 450 mm x 600 mm	31 mm x 465.8 mm x 600 mm
VII	30 mm x 450 mm x 1200 mm	31 mm x 465.8 mm x 1200 mm

Table 4: Range of school desks manufactured by the VAI programme (Crouse, 2016)

1. Primary combination desk  1065 x mm 790 mm x 650 mm	2. Secondary combination desk  1200 mm x 810 mm x 750 mm
3. Secondary single combination desk  600 mm x 810 mm x 750 mm	4. Primary single combination desk  600 mm x 790 mm x 650 mm
5. Lower primary double table (stackable)  1000 mm x 450 mm x 575 mm	6. Higher primary double table (stackable)  1000 x mm 450 mm x 650 mm
7. Secondary double table (stackable)  1200 mm x 450 mm x mm 750	8. Secondary single table (stackable)  550 mm x 450 mm x 750 mm
9. School desk top double IMAGE NOT AVAILABLE 1200 mm x 450 mm x 21 mm	10. School desk top single IMAGE NOT AVAILABLE 600 mm x 450 mm x 21 mm

3.2 Simsaw 6 software package

Simsaw 6 was used to calculate sawlog volume and volume recovery of sub-sampled trees (logs) of the invasive wood resource. The trees' (logs') volumes were incrementally reduced taking height at first major branching, taper, and sweep into account. Simsaw 6 is a powerful production planning software package developed by the CSIR (Council for Scientific and Industrial Research) in cooperation with Stellenbosch University. The software is a sawmill production simulation package which allows the user to input measured log dimensions or generate log dimensions which can be expected from a forest resource. Once the wood resource has been defined, the user can specify an array of different log sawing patterns across multiple production lines. The software allows the user to simulate critical 'what-if' questions. Recovery refers to the percentage of processed wood product attained in relation to a specified log resource. This is calculated in volume (m^3) and expressed as a percentage of the original log resource volume. The simulation helps to answer the following questions (Wessels, B. 2015, Wood Products Science 414, lecture notes distributed in the module Wood Products Manufacturing by Stellenbosch University, Stellenbosch, 2015):

- Which product mix will maximise profitability?
- Which log resource mix will maximise profitability?
- What effect will log and output product price changes have on profitability?

Simsaw 6 was used in the development of the SVCF not through its ability to test volume recovery iteratively, but rather through its ability to calculate log volume. However, the results of each stepwise reduction (or modification) of log dimensions from treatment data (laser calliper, photogrammetry, LiDAR) is tested for volume recovery by applying a standard sawing pattern. An optimum sawing pattern for each log class was developed and the volume recovery tested.

Simsaw 6 requires input information of the user if the user wishes to define non-simulated log dimensions (i.e. actual measured logs) and assign these logs to defined log classes. These log characteristics are:

- Small-end log diameter (cm).
- Log length (m).
- Log taper (mm/m).
- Log sweep (mm).
- Log ovality.
- Defect core of log (cm).

Log ovality is a measure of log roundness and is calculated by dividing the log's maximum big-end diameter by the perpendicular big-end diameter. This delivers a unitless value used by Simsaw 6. If ovality cannot be calculated due to insufficient information, a value of 1 can be used to bypass the log ovality characteristic. Defect core refers to defective core characteristics which negatively influences value recovery as it is related to log quality and not volume. If defective core information is not available, a value of 0 can be used. As defective core characteristics were not included in the scope of this project, a value of 0 was used. Table 5 below gives a summary of the minimum and maximum log dimensions that Simsaw 6 can process. If logs were longer than 10 m, they had to be bucked manually before input into Simsaw 6.

Table 5: Summary of minimum and maximum log parameters for inclusion into Simsaw 6 sawing simulations

Diameter (cm)		Length (m)		Taper (mm)		Sweep (mm)	
Min	Max	Min	Max	Min	Max	Min	Max
5	99	0.5	10	0	99	0	40

Simsaw 6 also requires an input of log classes to undertake sawing simulations. Each log class makes use of a defined sawing pattern; either an industry standard or an optimum pattern decided on by the user. The log classes were defined according to the desired output product dimensions (boards) used to manufacture eco furniture school desks.

The log classes listed below (Table 6) were used as a standard for the Simsaw 6 simulations. These classes will not necessarily be used by the respective VAI sawmills situated throughout South Africa.

Table 6: Log class dimensions used in the Simsaw 6 sawing simulation

Log class no.	Diameter (cm)		Length (m)		Taper (mm)		Sweep (mm)	
	Min	Max	Min	Max	Min	Max	Min	Max
1	5.0	22.9	0.5	10	0	99	0	40
2	23.0	44.9	0.5	10	0	99	0	40
3	45.0	80	0.5	10	0	99	0	40

Each log class (Table 6) had an associated sawing pattern with both log class and saw pattern remaining constant throughout every simulation to maintain consistency.

Figure 10, Figure 11 and Figure 12 below are examples from the Simsaw 6 software package illustrating the sawing patterns used for the three different log classes in the Simsaw 6 sawing simulations. The output products are shown; boards 30 mm thick, and 110 mm and 450 mm wide are delivered. Lengths of the output products are also shown, in some cases multiple boards were extractable along the length of the log, particularly in the centre of larger logs (Figure 11 and Figure 12). The cumulative board length comprising of several individual boards is then shown.

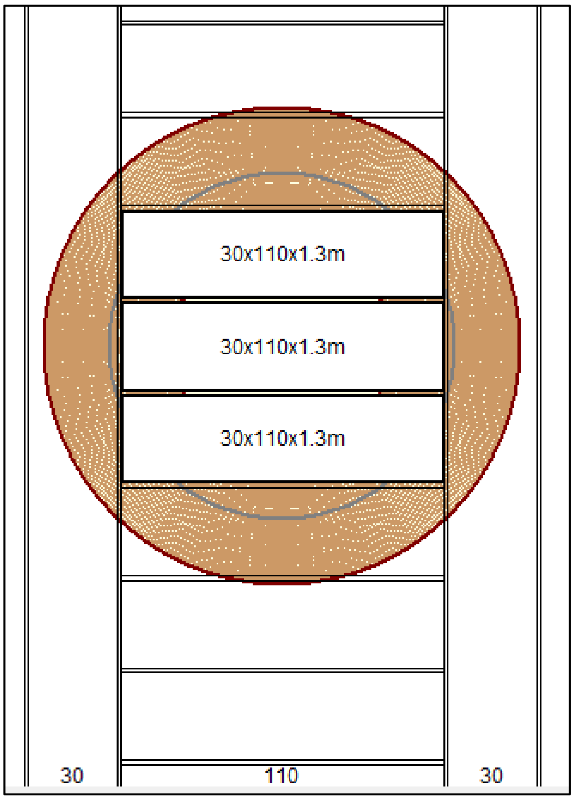


Figure 10: Example of sawing pattern used for first (smallest size) log class in Simsaw 6 simulations

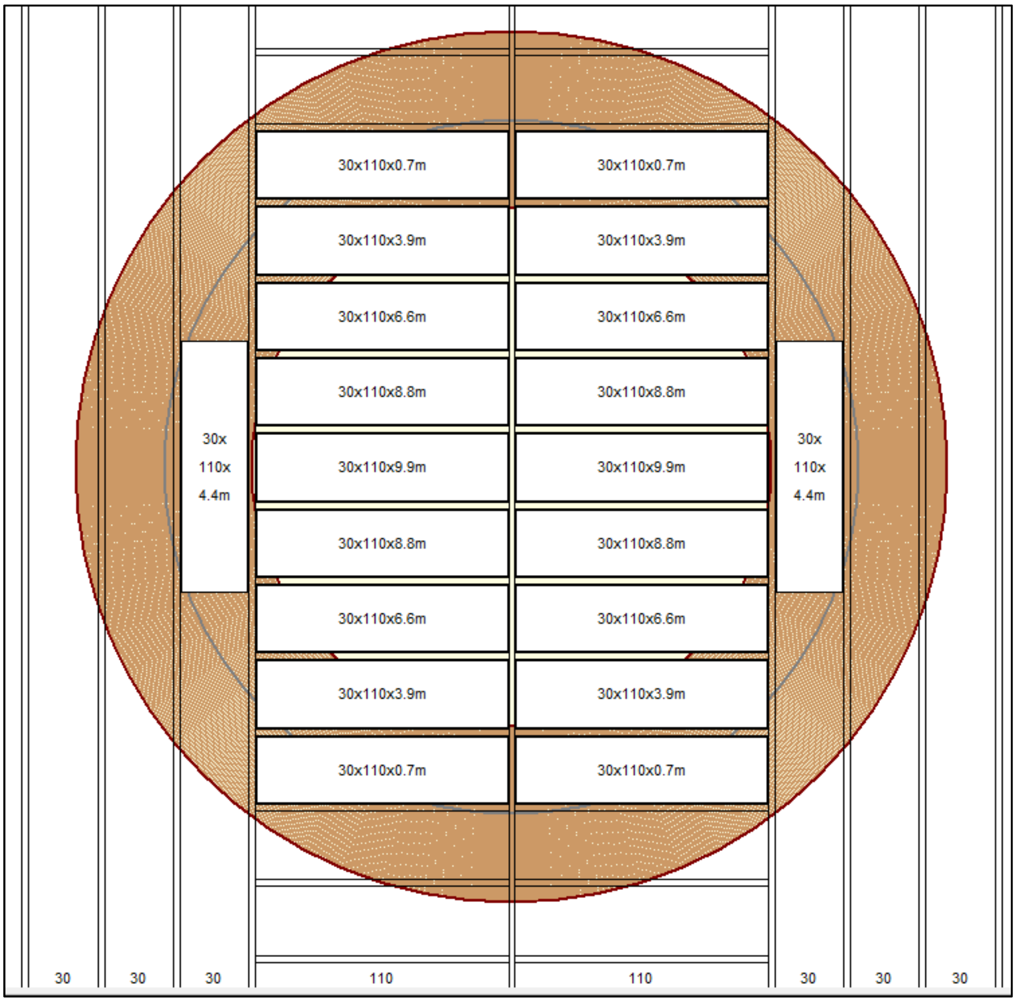


Figure 11: Example of sawing pattern used for second (medium size) log class in Simsaw 6 simulations

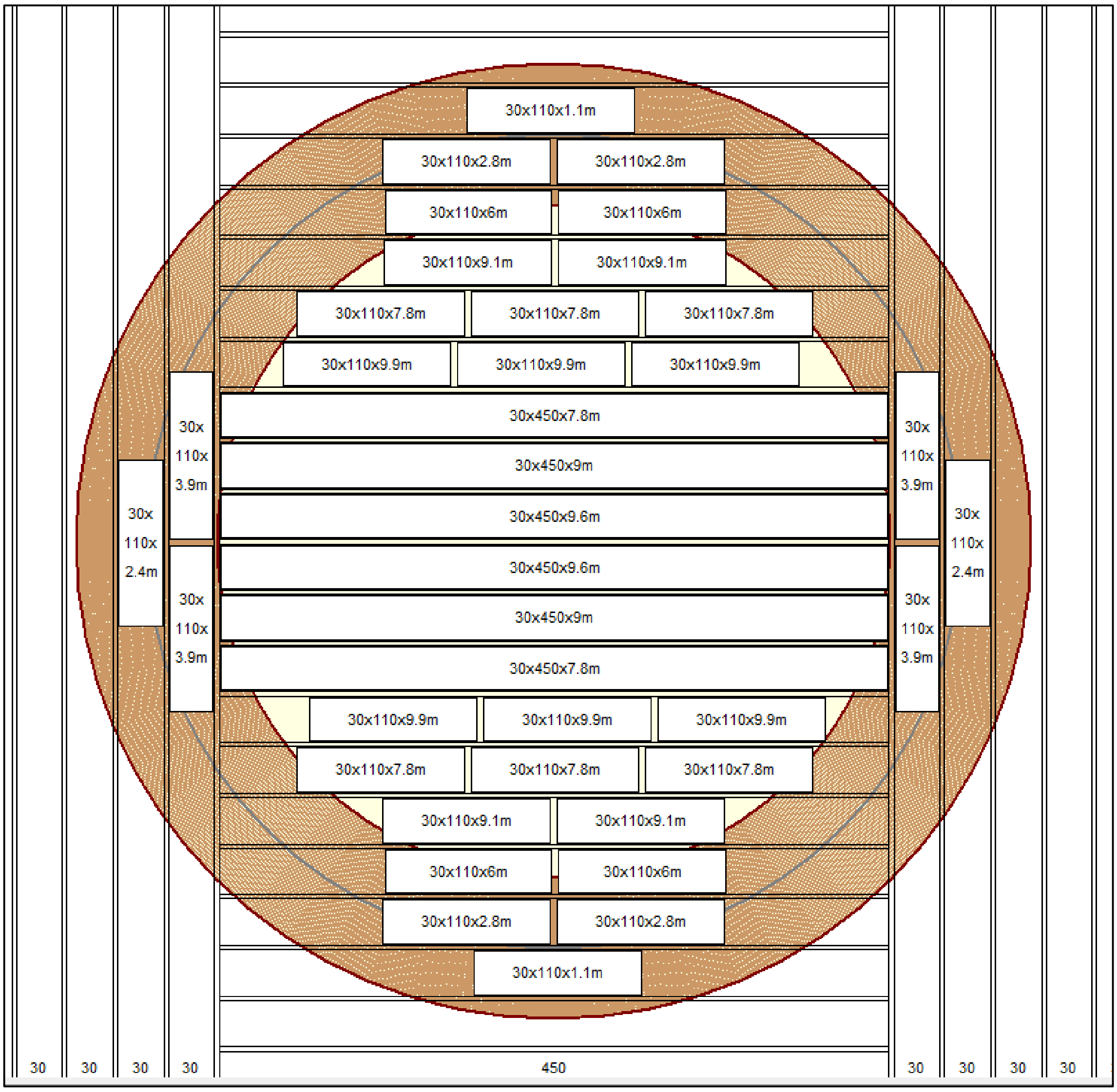


Figure 12: Example of sawing pattern used for third (largest size) log class in Simsaw 6 simulations

3.3 Delineation of study area

For this study, the Berg and Breede Rivers were chosen as potential river systems of interest. Both rivers are in the Western Cape Province of South Africa (within reasonable proximity to the University of Stellenbosch) (Figure 13). Both river systems have been identified as experiencing severe infestation of AIPs (Ruwanza, et al., 2013).

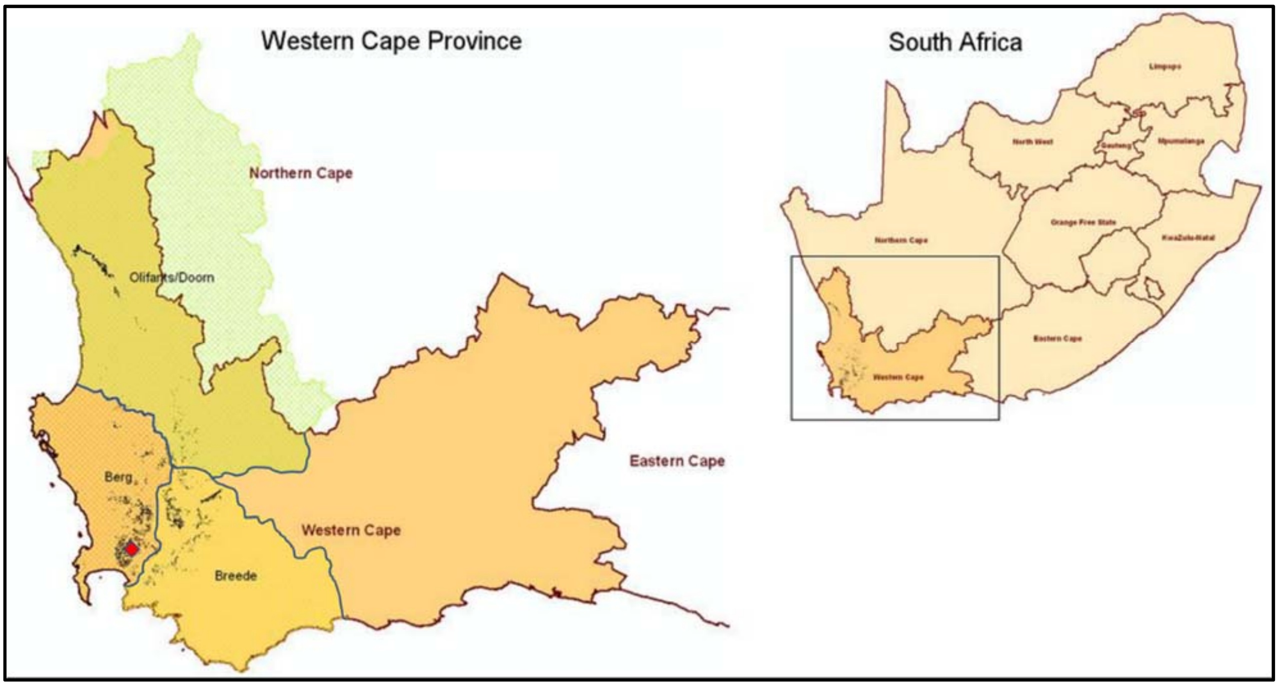


Figure 13: Overview of the location of the Berg and Breede River systems and their proximity to Stellenbosch (red diamond) (Klaasse & Jarmain, 2011)

The structure and properties of AIF stands along these river systems is not homogenous. The length of these rivers and issues of inaccessibility at several points meant that it was not possible to do exhaustive assessments of all trees along these rivers, and only selected areas could be studied. But to make decisions to this end effectively, it was considered necessary to understand the range of "types" of AIFs present, and then target specific instances of greatest importance for this study. Possible site types were limited by their proximity to the river bank. Sites adjacent to the river, within a buffer zone of maximum 100 m on either side of the river's edge were considered. Based on a combination of field visits where qualitative classifications of site density, vegetation type and dominant species were made, as well as characteristics of stands from aerial and satellite images of the rivers, three distinct, broad site types were identified. These were site type A - "Paarl farm", B - "Breede River", and C - "Lady Loch Bridge" (Table 7 and Figure 14). Site type A is of highest interest and value to the study because of the vegetation present (recognised foreign/exotic tree species), high stand density per hectare (number of stems occurring over given unit area) and similarity to a conventional plantation forest environment. This site therefore offered the highest possibility for the application of knowledge stemming from conventional plantation forestry in South Africa. It was therefore decided that site type A would be chosen as the focus site type for the study. Regarding foreign tree species, woodlands comprise mainly of indigenous tree species growing under natural or semi-natural conditions (although it may include some localized areas of self-seeded exotic species), but excludes planted forests and woodlots (Thompson, 1996). These sites can therefore be considered forests and woodlots comprising of foreign tree species. The decision to use 200 STPH as a classification characteristic was based on field visits to potential study sites where stand density and canopy cover was inspected visually. Site types A, B, and C, showed clear differences in stand density with 200 STPH decided on as a threshold characteristic for this study.

Table 7: Table listing 3 different site types (A – C) together with a visual description, GNSS coordinates of example sites, and classification characteristics observed along stretches of the Berg and Breede Rivers in the Western Cape Province of South Africa.

Site type	Description	Classification characteristics	GNSS coordinates of example sites
A	Trees grouped in large enough numbers and over large enough areas to be considered forests.	• STPH > 200 • Predominantly interlocking and continuous tree canopy	33° 32' 27.38" S 18° 56' 08.63" E
B	Rows of trees along stretches of river bank.	• > 8 trees in a row, resulting from planting or selective removal of other vegetation • > 15 m of river bank occupied by tree row(s)	34° 03' 51.00" S 19° 33' 16.00" E
C	Single trees scattered in an unordered pattern along stretches of river bank.	• STPH < 200 • Clearly discernible individual tree canopy • Only few trees compared to “full” tree population of site type A.	33° 37' 49.82" S 18° 58' 34.24" E

Figure 14: Google Earth (aerial) image of site type A (left) situated on the edge of a section of the Berg River system. The image illustrates the closed canopy characteristic of the site, similar to plantation forests. Site type B (top right) illustrating trees found in-line along the edge of the Breede River system. Site type C (bottom right) illustrating trees found scattered along the edge of the Berg River with individual tree canopies clearly discernible.

3.4 Detailed site measurements

A short-list of two type A candidate sites, identified as likely feasible for further study and intensive measurement, was subsequently created. These sites were found on both the Berg and Breede River systems and were decided on based on the following criteria:

- Site location and distance from Stellenbosch.
- Total area (ha).
- Vehicular accessibility.
- Permission from land owner to enter site;
- and site prioritised by NRM for clearing in near future.

Two candidate sites were visited and assessed with one final site, ''Paarl farm", selected for detailed measurements. The Paarl farm site forms part of a grain farm situated in the Paarl region of the Western Cape Province of South Africa (Figure 15).

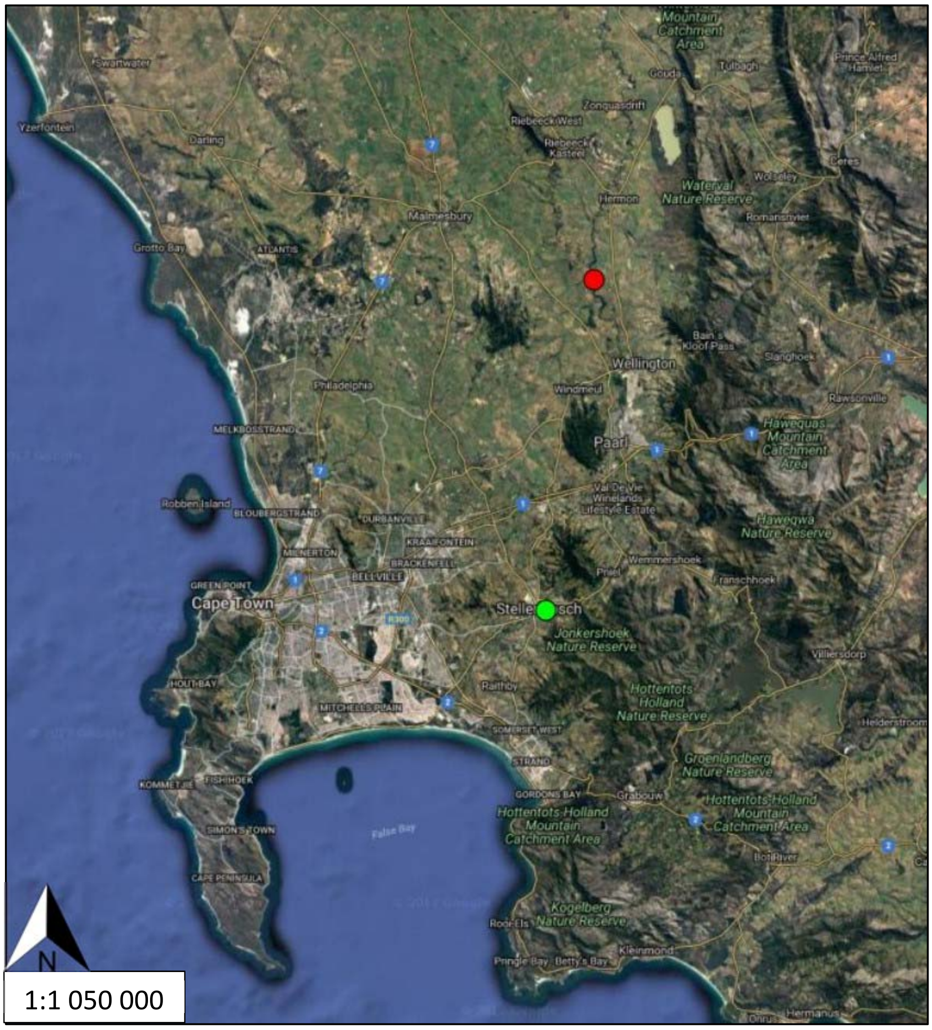


Figure 15: Google Earth (hybrid aerial) image of the location of Paarl farm (red) and Stellenbosch (neon green) in the Western Cape Province of South Africa. Paarl farm (red) is situated on the Berg River.

3.4.1 General sampling approach

At the selected ''Paarl farm'' site (hereafter referred to as "the study site"), a simple random sample of 22 circular 400 m^2 sample plots was laid out (Figure 16). The total sample corresponded to a sampling intensity of 8.25%, from the total forest area of 10.66 ha, as determined from boundary delineation from satellite images (Figure 16) of the study site (Howard, 2012). An open-source Geographical Information System (GIS) software package, Quantum GIS (QGIS) was used to create the simple random sample plot layout.

For the placement of sample plots, two constraints were imposed:

(a) a minimum spacing of 45 m between each plot to ensure that the plots would cover the entirety of the study site's spatial extent, and

(b) due to some of the practical concerns surrounding the correct implementation of boundary correction methods, a buffer zone of 11.28 m (equal to the plot radius) along the interior of the study site was created. These concerns arose mainly because of the unclear boundary line of the site and the applicable edge correction system to follow, such as the mirage plot method (Ducey, et al., 2004). This buffer would allow circular sample plots to be scattered throughout the compartment, never overlapping the boundary of the compartment. Coordinate readings from GNSS devices are known to distort as they face difficulties triangulating signal from satellites when traversing through wooded areas (Naesset, 2001). This was also a reason for creating the interior boundary buffer to mitigate GPS accuracy troubles.

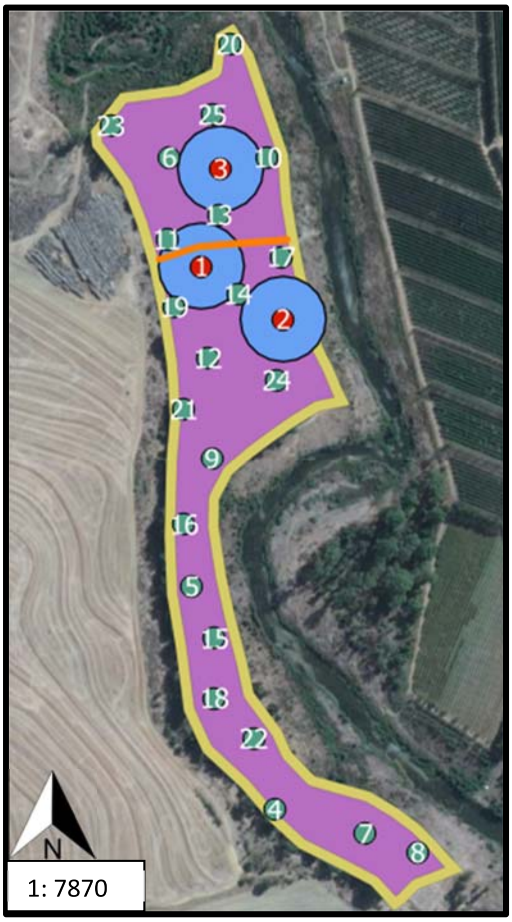


Figure 16: QGIS rendered image of the Paarl farm study site. Circular sample plot centre points are numbered 1 – 25. Purple represents the compartment interior while yellow represents the interior boundary buffer zone of 11.28 m. Orange represents the access road and buffer zone, approximately 5m wide. Light blue circles surrounding points 1 – 3 represent the minimum point spacing of 45 m between sample plots.

Full stand characterisation was not the objective of this study but rather it was aimed to understand how much volume loss would be expected relative to an ideal forest of the same species and stand density per hectare (i.e. a forest of "perfect" trees from which maximum recovery would be expected). The error from difficult boundary areas was considered undesirable and therefore avoided.

Points 11, 20, and 21 (Figure 16) were excluded as these were found to be either completely beyond the site boundary (point 11) or well within the interior buffer zone of 11.28 m (points 20 and 21). Figure 16 shows further ambiguity, for example, point 4 can be seen to fall well within the interior buffer, but once in-field it was found to be well within the site and clear of both the interior buffer and exterior boundary. The end of the tree canopy was used to discern the site boundary, in this case observed from an aerial image (Figure 16).

3.4.2 Basic plot measurements

Plots were located in-field using a Trimble Juno 3B GNSS device (Optron, 2010). Only when accuracy was at or below 2 m, plot position was confirmed and north direction established. The circular plot was laid out using a centrally positioned transponder with a Vertex® IV hypsometrer unit (Haglöf Company Group, 2017). Within each plot the following measurements/assessments were made:

- Diameter at breast height (1.3 m) was measured on all trees within the bounded plot using a DBH tape.
- Species was recorded for all trees within the bounded plot.
- On a sub-sample of minimum 5 trees per plot, height was measured using a Vertex IV hypsometer. The trees were chosen to capture the DBH distribution.
- In addition to tree height, the numbers of stems per tree were also recorded.
- Signs of damage, stem split and coppice regrowth from previous unsuccessful clearing operations were noted.

3.5 Sub-sampling

From the full set of 22 sample plots on the study site, a set of intensive scans and detailed up-the-stem measurements were made on selected trees in a sub-set of sample plots. These were:

- Photogrammetry using digital images of trees obtained with a Nikon Coolpix A100 camera (Nikon Corporation, 2017) from multiple positions around the tree stem. Carried out on 14 selected trees in eight of the sample plots.
- Terrestrial LiDAR (light detection and ranging) scanning of the whole plot. Carried out on two of the plots.
- Measurements at multiple points up the stem with laser callipers. Carried out on selected trees in all 22 plots.

3.5.1 Laser calliper treatment: taper and butt-log length

A Haglöf calliper (Haglöf Company Group, 2017) fitted with a pair of lasers (marketed as "gator eyes"; Figure 17) was used to measure upper stem diameters. The calliper has lasers positioned under each arm that are pointed at parts of the stem out of reach from a practitioner on the ground. The calliper is opened until each laser beam is seen to be on the very edge of either side of the stem profile where a measurement is required. A subset of trees from all 22 sample plots on the study site were selected based on the study site's diameter (DBH) distribution and included trees initially measured for height in the development of DBH-height regressions. The height limit to which the calliper can measure is defined mostly by upper stem visibility. The laser point becomes difficult to position if, for example, foliage obstructs the laser. 32 *Acacia mearnsii* and 94 *Eucalyptus camuldulensis* trees were measured with the gator eyes on the study site. 20 *A. mearnsii* and 66 *E. camaldulensis* trees were chosen for DBH-height measurements.

The trees within the plots were chosen according to the diameter distribution of the two dominant tree species, *Eucalyptus camaldulensis* and *Acacia mearnsii* present on the site. Trees above 11 cm DBH were prioritised for selection as these represent higher value potential saw logs. The measurement of upper-stem diameter is time consuming and for this reason, not all trees were measured on which DBH was available. A weighted sampling method based on the study site's diameter (DBH) distribution for both *Eucalyptus camaldulensis* and *Acacia mearnsii* (Table 19) was used (including the trees initially measured for height). A script was developed in the R system of statistical computing (RStudio, 2016) to develop incremental diameter classes (breaks). These were first decided on incorporating the minimum (>5.0 cm) and maximum diameters measured for each species. The method would then produce an output number of 'measurable' trees per diameter class. The output number of trees per diameter class is dependent on the total number of trees belonging to that diameter class, the total number of trees that one would like to measure in total (29 *Acacia* and 93 *Eucalyptus*) and in each diameter class, the total number of trees per species measured in the inventory of 22 sample plots (±215 and ±425), and the number of classes decided on to start the process.

Figure 17: Haglöf laser calliper used to measure upper stem and branch diameters measurement

In addition to the trees initially chosen for height measurements, trees were also chosen according to visually noted stem form characteristics such as splitting and curvature as well as straightness. It can however be noted that the trees initially selected for DBH-measurements (constituting majority of the selected trees) were chosen to incorporate as much height and DBH variation on the study site as possible. Upper stem diameter at first major branching was measured with heights at measurement points recorded by a Haglöf Vertex IV (Haglöf Company Group, 2017). Upper stem diameters at key heights as well as essential information about variable form were captured in detail in a field notebook for later processing (Figure 18). This height at first major branching refers to a position on the stem where branching has caused the log to split off; above which no further part of the stem can be used in a sawmill. The height at first major branching could also be the highest possible measurement point on the stem due to problems of upper stem visibility resulting from low hanging branches and foliage. In some cases, more merchantable stem above this point was noticed but a measurement could not be taken using the laser calliper. Stem sections above this first major branching position were therefore disregarded. Injuries on the stem were not taken into consideration. Merchantable stem sections shorter than 10 m in length were used as sawlogs directly. Merchantable stem lengths longer than 10 m were bucked into sawlogs of 10 m (starting from the top and moving downwards) with the remaining lengths also used as sawlogs, but only if the remaining length was at least 0.5 m long. The remaining length was disregarded if it was not at least 0.5 m in length. After bucking, the small-end log diameter of the remaining log length was calculated by using the constant-form taper value for the log (mm/m) and calculating a new diameter at a length of 10 m.

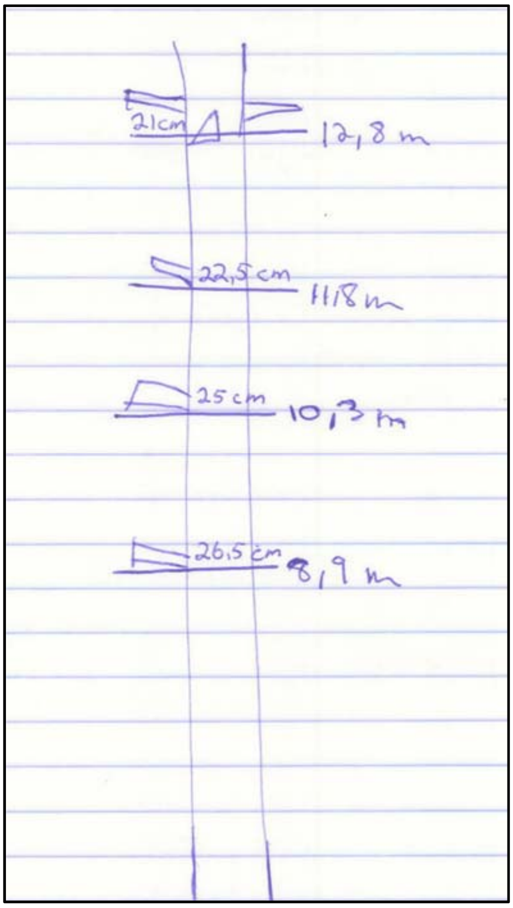


Figure 18: Example of field notes used to capture laser calliper data of upper stem diameters. A diameter measurement is recorded together with a height measurement.

3.5.2 Photogrammetry Treatment: Butt-log length

In eight of the plots, 14 trees were selected for photogrammetry. Trees were selected according to visually noted stem form characteristics such as splitting and curvature as well as straightness. Trees were chosen which in total would constitute a representative sample of the site's variation in stem form. *Eucalyptus* was the only species chosen for photogrammetry from the population because of the overwhelmingly high majority of *Eucalyptus* trees present on the site over other species.

For obtaining images, red and white incrementally marked poles were placed around the tree in a square configuration (Figure 19). Each pole is approximately 1.2 m in length and is equipped with a level-finder (Figure 19). Poles were placed at least 1.5 m from the centre of the tree so as to not obstruct the tree stem when photographed, but still well within the frame of the photograph. The poles allow for scale determination in the images. At least 40 images of each tree were obtained, from multiple positions, maximum 0.5 m between positions, to achieve a sufficient level of overlap. Photogrammetric reconstruction software (Agisoft, 2017) was used, based on derived scales, to derive stem length. The photogrammetric reconstruction creates a 3-dimensional interactive object from multiple 2-dimensional images of the subject. The Structure from Motion (SfM) technique makes this possible. The positioning of field hockey balls atop of the poles allows for common reference points to be established, allowing for images to be registered to one another.

Figure 19: Images showing the final layout of the scene necessary to capture photogrammetric data. Left image shows how more than one stem can be captured in one scene, in this case both stems originate from the same stump below the soil surface. Right image shows the conventional single-stemmed set up. Both images show how the incrementally marked poles and field hockey balls are clearly visible and discernible. Each red and white increment on the pole is 30 cm in length and immediately stands out to the examiner. The field hockey balls are then placed on top of each pole and the distance from one hockey ball to another is measured. The laser emitter of the Bosch distance measuring device should be positioned just above the very centre of the hockey ball with the laser striking the front of the adjacent hockey ball.

Agisoft PhotoScan Professional is a photogrammetry software package and for this study it was used to register multiple tree stem photographs to each other. The photographs were taken from various angles, encircling the subject tree. The photos were then registered to each other, merging the various views of the tree into a 3-dimensional object. To achieve this, the subject tree was isolated with all other irrelevant vegetation removed. Figure 20 below illustrates the full extent of photographs taken of the subject tree.

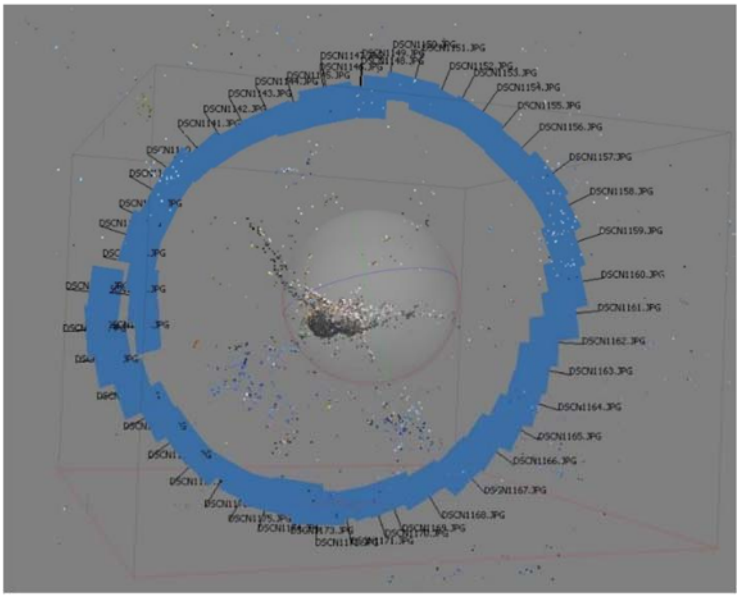


Figure 20: Extract from Agisoft Photoscan Professional showing the various overlapping photographs (full rotation) taken of the subject tree. These photos are merged to create a 3-dimensional image of the subject tree.

Once the tree stems were successfully isolated, a point cloud was exported and further analysis undertaken in CloudCompare, an independent, free, and open source software product designed to process 3D point cloud data, triangular meshes and calibrated images (CloudCompare, 2017). These isolated stems can be considered butt logs, with the stem's height considered a length, creating a butt-log length.

3.5.3 Terrestrial LiDAR Treatment: Stem Sweep

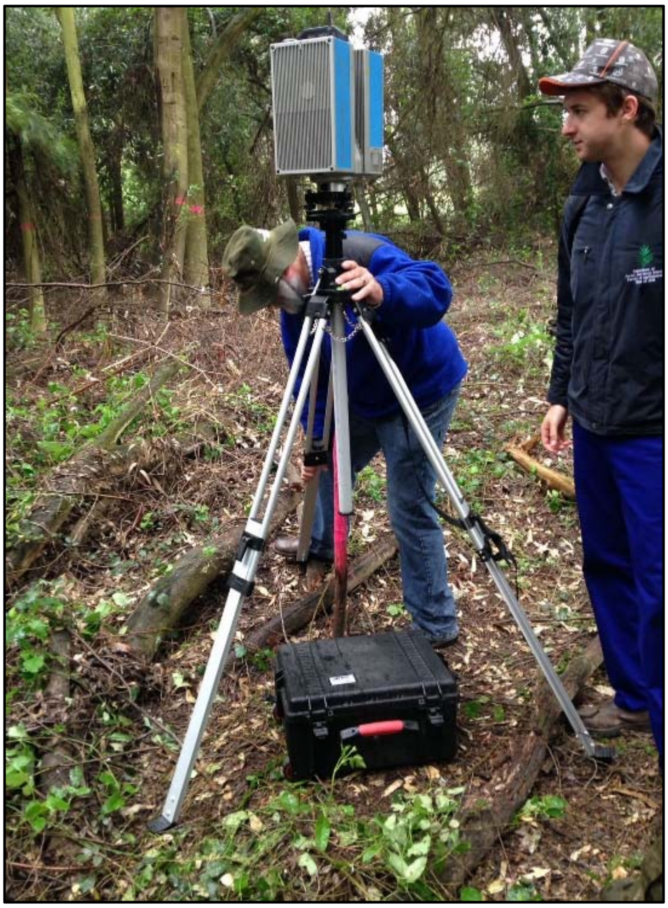


Figure 21: Z+F Imager® 5010X high-resolution (LiDAR) scanner, here operated by Anton Kunneke and Brendan Marais of Stellenbosch University.

A high-resolution Z+F Imager® 5010X was used to capture point clouds of sample plots to extract important individual tree metrics; DBH, stem taper, stem sweep, and height (stem length). The high-resolution scanner was used in two of the 22 plots. The plots were selected because they exhibited lower undergrowth density than others. Low undergrowth density is preferable for scanning (Kelbe, et al., 2013). Site conditions such as tree density (STPH) and undergrowth density can affect the level of detail captured by the machine (Radtke & Henning, 2006). The goal was to capture as much site variability in tree stem form as possible.

The LiDAR/laser scanner machine was positioned in five locations to allow the full recreation of form and structure of all trees within the plot (Figure 22). From the plot centre the four cardinal directions, north, south, east, and west, were identified with 5 m measured out in each direction. The machine was positioned at the centre and the first scan taken. The machine was then moved 5 m in each direction with subsequent scans taken at each point.

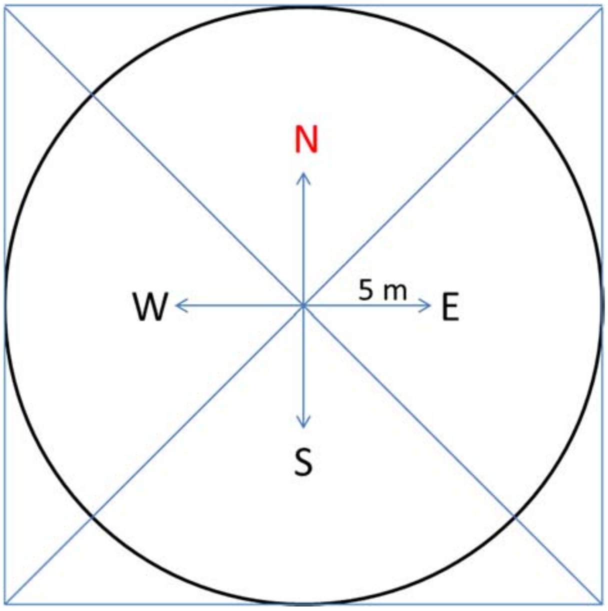


Figure 22: Schematic representation of the 5-scan layout used in capturing sample plots using a LiDAR scanner. The first scan is taken at the plot centre with 4 consecutive scans taken 5 m from the plot centre in each cardinal direction.

Z+F LaserControl® (Zoller + Frolich, 2017) proprietary software was used to manually register the scans to each other and deliver point cloud data of all 5 scans in a unified coordinate system (m). Using R studio, a simple R script was developed to extract metrics of height, stem diameter and sweep from tree point cloud data isolated from high-resolution LiDAR scans. The script uses the point cloud data, calibrated to metres, and divides the isolated stem into discs at 10 cm intervals up the stem. The script then fits a circle to the points constituting the stem face such that the radius of the circle is dependent on the maximum number of points that the circle's circumference can pass through (Figure 23). This is useful in that the script can determine the stem's diameter at specified heights. The highest number of points in contact with the fitted circle's circumference is accepted to deliver the stem diameter at that height. The circle's radius is then doubled to deliver diameter. This process is repeated at each 10 cm interval up the stem, until a height is reached where no more points representing the tree's stem are found. This can be due to obstructions in-field, such as branching or foliage or other trees in front of the subject tree.

Figure 23 below shows this incremental circle fitment up the length of the tree. Although top view relative to the base of the log is shown in the image, stem height is discernible here because of the sweep isolated log exhibits, giving the effect of lean, and therefore height. This log represents an extreme case of sweep; identifiable at three regions up the stem (base, middle, and top), which is pointed out with the help of red arrows.

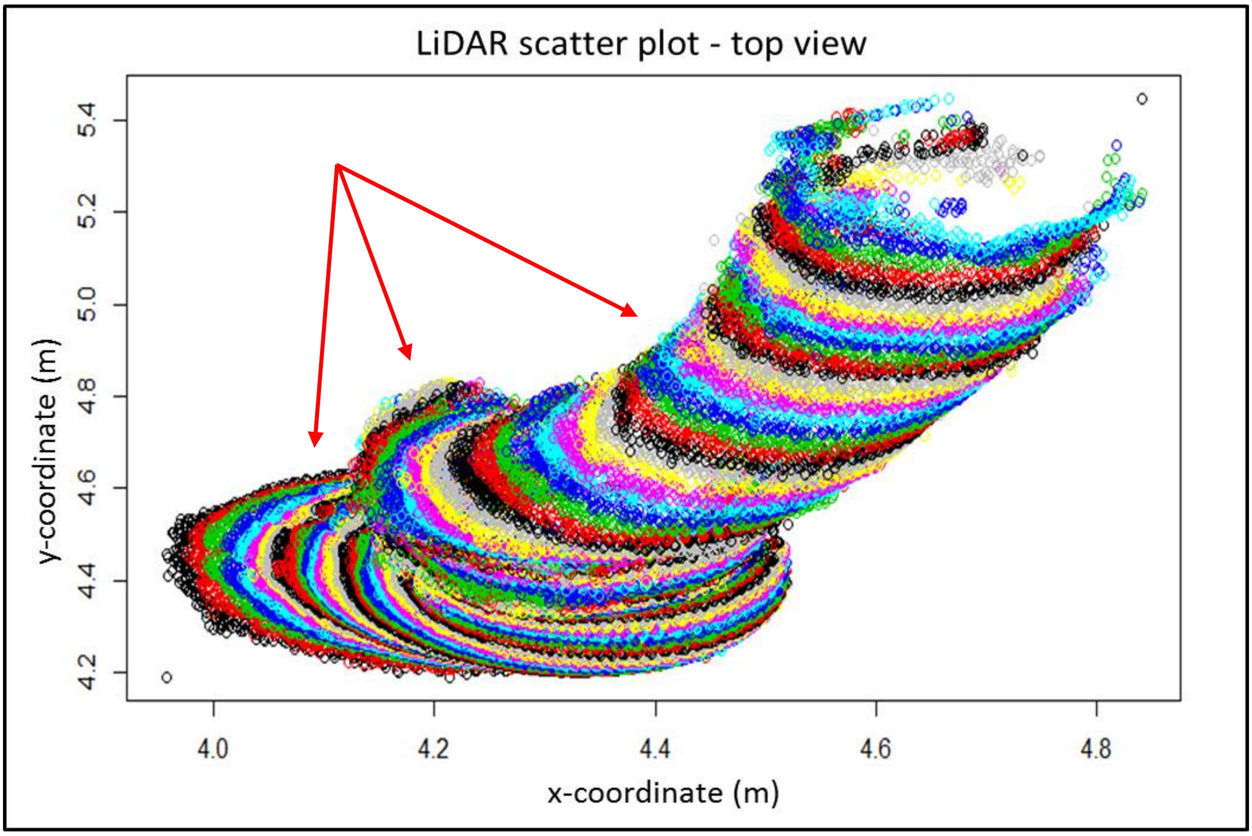


Figure 23: Scatter plot used to visualise the fitment of a circle over every 0.1 m interval up the stem profile. In this plot, top view is shown with x-and-y coordinates (m), but z-coordinates (height in metres) excluded. The log shows extreme sweep delivering a leaning effect relative to the top viewing point.

Sweep was assessed at 10 cm intervals up the stem. A linear regression joining the top and bottom centre points of the circles fitted up the stem serves as the imaginary straight log line – as if the log were perfectly true (Figure 24). The regression line is also plotted with the same intervals as height (10 cm) and the residuals of the x-or-y coordinate (m) vs. height (m) line and the regression line is used to define log sweep. In this study, sweep was considered in two orthogonal planes (x-and-y axes). Figure 24 below depicts this sweep calculation in the y-axis.

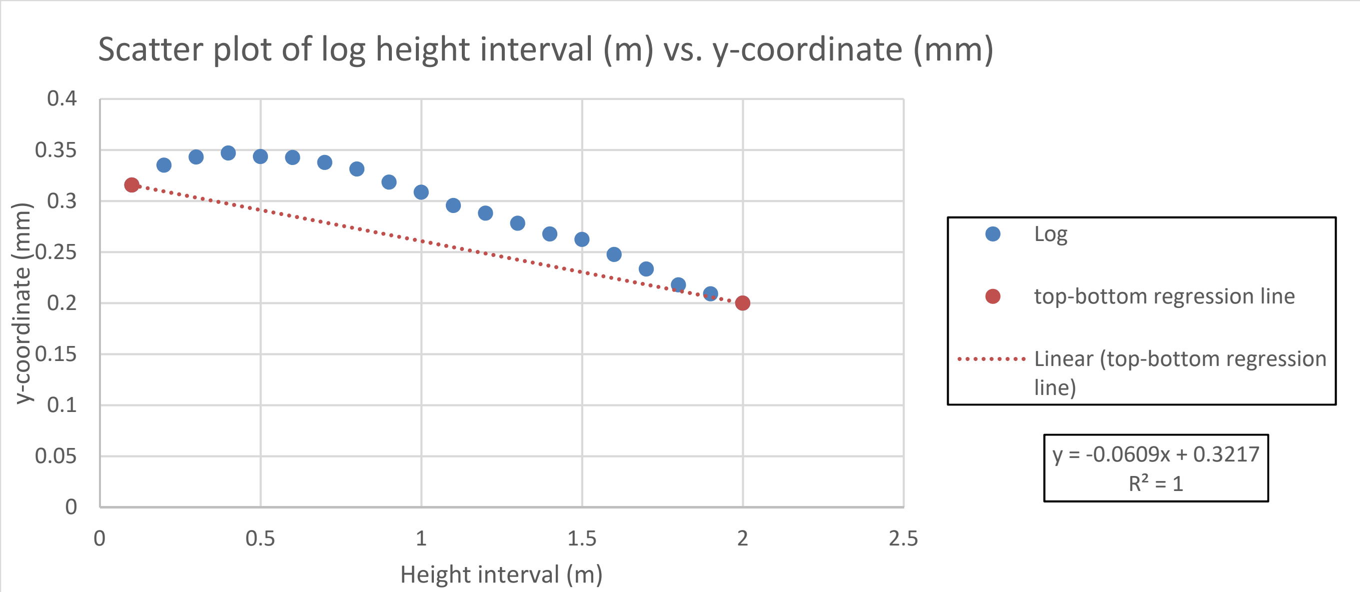


Figure 24: Graph showing the straight regression line connecting the centre point of the top of the log to the centre point of the bottom. The centre points of every fitted circle at 0.1 m intervals up the length of the log to a height of 2 m are also shown.

Simsaw 6 is used primarily for calculating sawn output product volumes with sweep not affecting sawlog input volumes. For this reason, sweep will have to be excluded from the development of a SVCF, but the results of subsequent sawing simulations with and without log sweep is presented. This is used to indicate the sawn product losses one might expect if the effect of sweep is not minimised through bucking. More information on the Simsaw 6 software package is presented in section 3.2.

3.6 Standing Volume

3.6.1 Regression height

In the initial pilot inventory study, DBH was measured on all trees, but only a select few trees had measurements of both DBH and height. This was for practical reasons, as measuring height is time-consuming. Height of the five trees closest to the centre of the sample plot were measured and only if the top of the tree was clearly visible. If the top was not clearly visible the next closest tree was measured. *E. camaldulensis* trees outnumbered *A. mearnsii* trees and to ensure that enough of the minority species were measured, two of the five were *A. mearnsii*. On plots where no *A. mearnsii* occurred, five *E. camaldulensis* trees were measured. Heights for trees on which it was not measured were ascertained by substituting DBH into a regression function of DBH and height. This is standard practice in forest inventory and possible because of the strong relationship between DBH and height that exists (Kassier, 2011). A separate model predicting height from DBH was developed for each of the (two) dominant species at the site. From these models, heights from all trees in the sample were calculated, for input into the volume estimation model. Using Microsoft Excel, different regression models were investigated (exponential, power, linear, logarithmic, polynomial). The model decided on for each species showed the best coefficient of determination (R^2) value between DBH and height.

3.6.2 Individual tree volumes

The essential first step in the study was to determine an estimate of total merchantable standing volume for the trees. This "control" volume is a representation of possible maximum volume recovery from the given wood resource, assuming trees whose volume can be estimated with published equations. To this end, the Schumacher and Hall logarithmic tree volume equation was used (Schumacher & Hall, 1933) with parameters developed for *A. mearnsii* (Schönau, 1972) and *E. camaldulensis* (Bose, 2009), which requires an estimate of tree-level DBH and height to get volume to 7.5 cm upper stem diameter (Table 8)

$$lnV = b_0 + b_1 \ln(\mathrm{DBH}) + b_2 \ln(\mathrm{Ht.}) \qquad \textbf{Equation 1}$$

Table 8: Coefficients for use in Schumacher and Hall (Equation 1) for *Acacia mearnsii* and *Eucalyptus camaldulensis* (Bredenkamp, 2012)

A. mearnsii		*E. camaldulensis*	
b0	-10.916	b0	9.350
b1	1.953	b1	2.012
b2	1.232	b2	0.691

3.6.3 Stand volume

Standing merchantable volume per hectare (m^3/ha) was estimated for all trees (diameter at breast height > 5 cm) of both species measured in the inventory of the study site (22 sample plots, 400 m^2 each) to the total stand area of 10.66 hectares. Individual volumes for all measured trees were averaged and upscaled (from plot area of 0.88 ha to 1.00 ha) to deliver volume per hectare (m^3/ha), and then to stand area (10.66 ha). Upscaling from plot volume to stand volume was therefore carried out according to area, using the volume per hectare (m^3/ha) for each species.

3.7 Sawlog volumes

With only DBH and height information, it is necessary to rely on assumptions about taper. This was taken to an upper stem cut-off diameter of 7.5 cm for the purposes of defining log images for input into Simsaw 6. Log length for input to Simsaw 6 is taken as tree height at an upper-stem diameter of

7.5 cm. Species-specific taper equations for *Eucalyptus camaldulensis* and *Acacia mearnsii* were used to define the baseline log images (Bredenkamp, 2012).

3.7.1 Height determination at upper diameter of 7.5 cm

Demaerschalk's constant-form factor taper function (Demaerschalk, 1973) and Max and Burkhart's segmented polynomial function (Max & Burkhart, 1976) were used to determine height for an upper stem diameter of 7.5 cm. Maximum tree height is limited by regression height, calculated in the first iteration of the control variable. These upper stem diameters were used to calculate a value for taper (mm/m) and big-end log diameter needed as input in Simsaw 6.

3.7.2 *A. mearnsii*

Demaerschalk's constant-form factor taper function:

$$d_u^2 = 0.9843dbh^2\left(\frac{H-h}{H}\right)^{1.2518}$$ **Equation 2**

3.7.3 *E. camaldulensis*

Excel solver was used to determine the height at which the upper diameter is 7.5 cm from the Max and Burkhart segmented polynomial function due to the much greater complexity of an analytical solution:

$$d_u^2 = dbh^2\left[-3.547\left(\frac{h}{H}-1\right)+1.683\left[\left(\frac{h}{H}\right)^2-1\right]-1.198\left(0.781-\frac{h}{H}\right)^2 I_2+55.754\left(0.121-\frac{h}{H}\right)^2 I_2\right]$$ **Equation 3**

$I_i = 1\ if\ \frac{h}{H} \leq \propto_i\ ,\ 0\ if\ \frac{h}{H} > \propto_i$ (i = 1, 2)

3.8 Butt-log length/height reduction: Laser calliper

As mentioned in Figure 9, a subset of the control sawlogs' volumes were reduced to a merchantable cut-off height based on measurements taken using the gator eyes laser calliper (both *A. mearnsii* and *E. camaldulensis*). The taper values for the control logs (calculated using Equation 2 and Equation 3) to the cut-off diameter of 7.5 cm were used to interpolate a new cut-off diameter (small-end diameter) for the reduced log length. The reduced log length represents a merchantable height to a variable cut-off diameter; measured height at first major branching. Only the control sawlogs which were also measured with the laser calliper were reduced taking this merchantable height into account and run through Simsaw 6. Figure 25 below shows how the control sawlogs were defined to a height corresponding to a top-end diameter of 7.5cm (using Equation 3), with subsequent reductions in volume resulting from height and diameter measurements taken at first major branching. These measurements were taken lower down the stem, ultimately resulting in less utilisable sawlog volume.

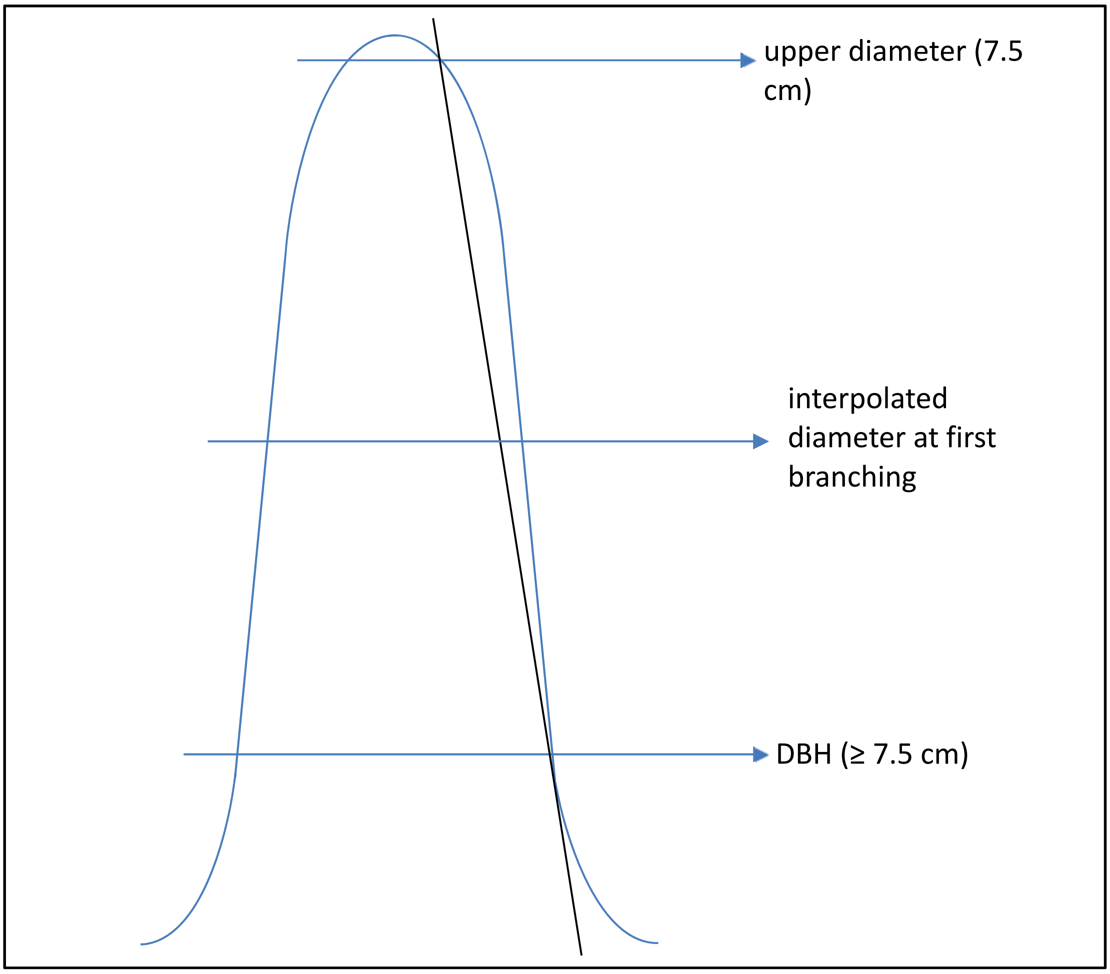


Figure 25: Schematic showing the reduction for height at first major branching and interpolation of diameter using a species-specific taper function interpolated down the stem to height at first major branching for trees measured with the laser calliper.

3.9 Constant-form taper modification: Laser calliper data

Tree data gathered using the 'gator eyes' laser calliper was used to provide an actual taper value to compare to modelled data when inputting log dimensions into Simsaw 6 simulations. First, taper values derived from Equations 2 and 3 were used to calculate (interpolate) a new small-end log diameter for the control sawlogs at the same height the laser calliper measured upper stem diameter at first major branching. Second, for every upper stem diameter measured using the laser calliper, stem height at that point was also measured. This information was used to develop a laser calliper derived constant-form factor value for each log's taper. The highest point at which a diameter could be measured becomes the log's total length. Taper was averaged over the log's total length from diameter at height 0.1 m, to the measured upper diameter. The calliper derived taper values were then used in the modified log images for both *E. camaldulensis* and *A. mearnsii* in Simsaw 6.

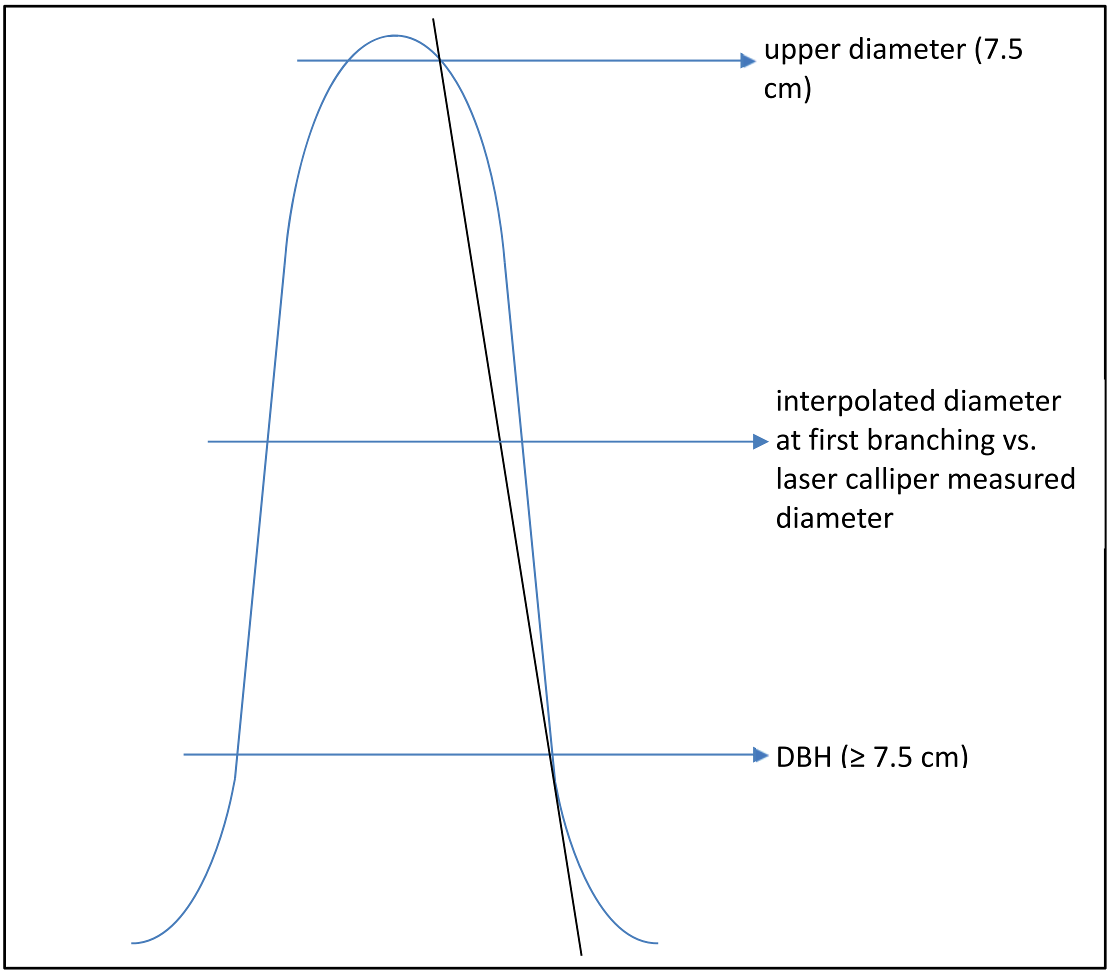


Figure 26: Schematic showing the modification of taper using a species-specific taper function interpolated down the stem to height at first major branching against the diameter measured at first major branching using the laser calliper.

3.10 Sampling Analysis

In addition to carrying out detailed sampling and sub-sampling of the forest resource for the development a SVCF, tree size variability was analysed towards better understanding sampling requirements for adequate precision. This will give WfW/NRM officials insight into the design and implementation of future invasive forest inventories. Several statistical estimators were used in the sampling analysis to test the accuracy and precision of the gathered measurements.

Accuracy refers closeness of a measurement or estimate to the true value. More broadly, it is the degree to which a statement or quantitative result is to the truth. Precision refers to the relative freedom from random variation. In sampling, it is quantified by the standard error and relates to the degree of clustering of sample values about their own average or the reproducibility of an estimate in repeated sampling (Schreuder, et al., 1993).

The efficiency of the sampling process was investigated to show that for an estimate of the population variance, given the desired precision (10%), a theoretical number of plots (n) of a given size would be needed. To this end, three avenues were investigated (1) to what extent does the inventory's precision change with the same number of sample plots, but with different area sizes (m^2) per sample plot, (2) to what extent does the inventory's precision change with the same area size of the sample plots, but with a different number of sample plots, and (3) which change affects the precision of the inventory to a lesser extent, and provides an alternative for more efficient and feasible sampling implementation?

An evaluation of the size of sample plots (100 m^2, 200 m^2, 300 m^2, 400 m^2) was carried out, followed by an evaluation of the quantity of sample plots (ranging from 2 to 50) using only the data gathered in the inventory of 22 sample plots 400 m^2 in size each. Then, a combination of both sample plot size and quantity, based on the number of sample trees per plot, and its effect on the inventory's precision are presented with an optimum sample plot size and number decided on. The results will present a recalculation of the theoretical number of plots, based on the number of trees per plot to reach a desired precision level of 10%. Relative standard error is used to represent precision. Table 9 presents the various statistical formulae and their symbols (Table 10) used in the sampling analysis.

Table 9: Formulae used in sampling analysis

Description	Formula
Variance	$S_y^2 = \frac{\Sigma_{t-1}^n (y_t - \bar{y})^2}{n-1}$
Estimated Standard Deviation	$S_y = \sqrt{\frac{\Sigma_{t-1}^n (y_t - \bar{y})^2}{n-1}}$
Estimated Standard Error	$S_{\bar{y}} = \frac{S_y}{\sqrt{n}}$
Estimated error variance	$S_{\bar{y}}^2 = \left(\frac{S_y}{\sqrt{n}}\right)^2$
Relative Standard Error	$A = rel.standard\ error_x = \frac{S_{\bar{y}_n}}{\bar{y}} * 100$
Expansion Factor (used to scale from 100 m^2/200 m^2/300 m^2/400 m^2 to 10000 m^2)	$Expansion\ factor = \frac{1000m^2}{Area_i}$
Recalculation of theoretical number of trees/plots to reach a desired precision (10%).	$n = \left(\frac{t_{\alpha,v}.S_{\bar{y}}}{A}\right)^2 = \frac{t^2.S_{\bar{y}}^2}{A^2}$

Table 10: Symbols and their meanings used in statistical equations

Symbol	Meaning
n	Number of elements in sample
$\bar{y}$	Estimated mean of the i-th value
A	Precision level
t	t-value from Student's t table (1.96)
v	Degrees of freedom (n-1)
α	Error probability (2-tailed, 0.05)
$Area_i$	Area of i-th sample plot (m^2)
x	Relative Standard Error (%)

To test the efficiency of the inventory regarding the study's precision will require a reduction in plot size. This efficiency was analysed for the variables basal area (BA) and volume (standing). This can be achieved using the tree's distance to sample plot centre measured in-field. With these distance measurements, plot size reductions were simulated and trees systematically excluded from the plots to simulate smaller plots with fewer trees. The relevant expansion factor is used to recalculate the BA per hectare (m^2/ha) and subsequent volume per hectare (m^3/ha) for plots of varying sizes (and therefore radii) (Table 11). Because this study is focused on estimates of standing volume more than BA, it was decided that volume would account for the final consideration regarding sampling efficiency.

Table 11: Expansion factor values required to scale various sample plot sizes to 1 hectare

Sample plot radius (m)	Sample plot area (m^2)	Expansion factor
5.64	100	100
7.97	200	50
9.77	300	33.33
11.28	400	25

Chapter 4: Results and Discussion

4.1 Plot measurements

Approximately 430 *E. camaldulensis* and 215 *A. mearnsii* trees (DBH ≥ 5 cm), were measured over 22 sample plots on the study site. Sample plot area totalled 0.88 ha. A summary of these measurements is presented in Table 12. On a per hectare basis, - *Eucalyptus* outnumbers *Acacia* roughly 2:1 (Eucalyptus makes up 65% and *Acacia* 35% of the total 640 trees (DBH ≥ 5 cm) measured in the stand inventory of the study site) but represented roughly 7:1 greater BA per hectare. *Eucalyptus* quadratic mean stem diameter was almost double that of *Acacia*.

Table 12: Summary of measurements taken over 22 sample plots 400 m^2 in size on the study site

Species	*A. mearnsii*	*E. camaldulensis*
Quadratic mean DBH (Dq cm)	10.43	19.68
STPH	245	486
Stand BA (m^2/ha)	2.09	14.78

Figure 27 below shows the diameter distribution for *E. camaldulensis* and *A. mearnsii* on the study site. *Eucalyptus* ranged predominantly between 5 cm and 61 cm with some large trees measured (e.g. one tree has a DBH of 94 cm), while *Acacia* ranged between 5 cm and 31 cm with a large tree of DBH 40 cm measured. The distribution showed a marked peak to the left of the distribution, similar to what would be expected in a natural forest environment characterised by active recruitment of young trees (Westphal, et al., 2006).

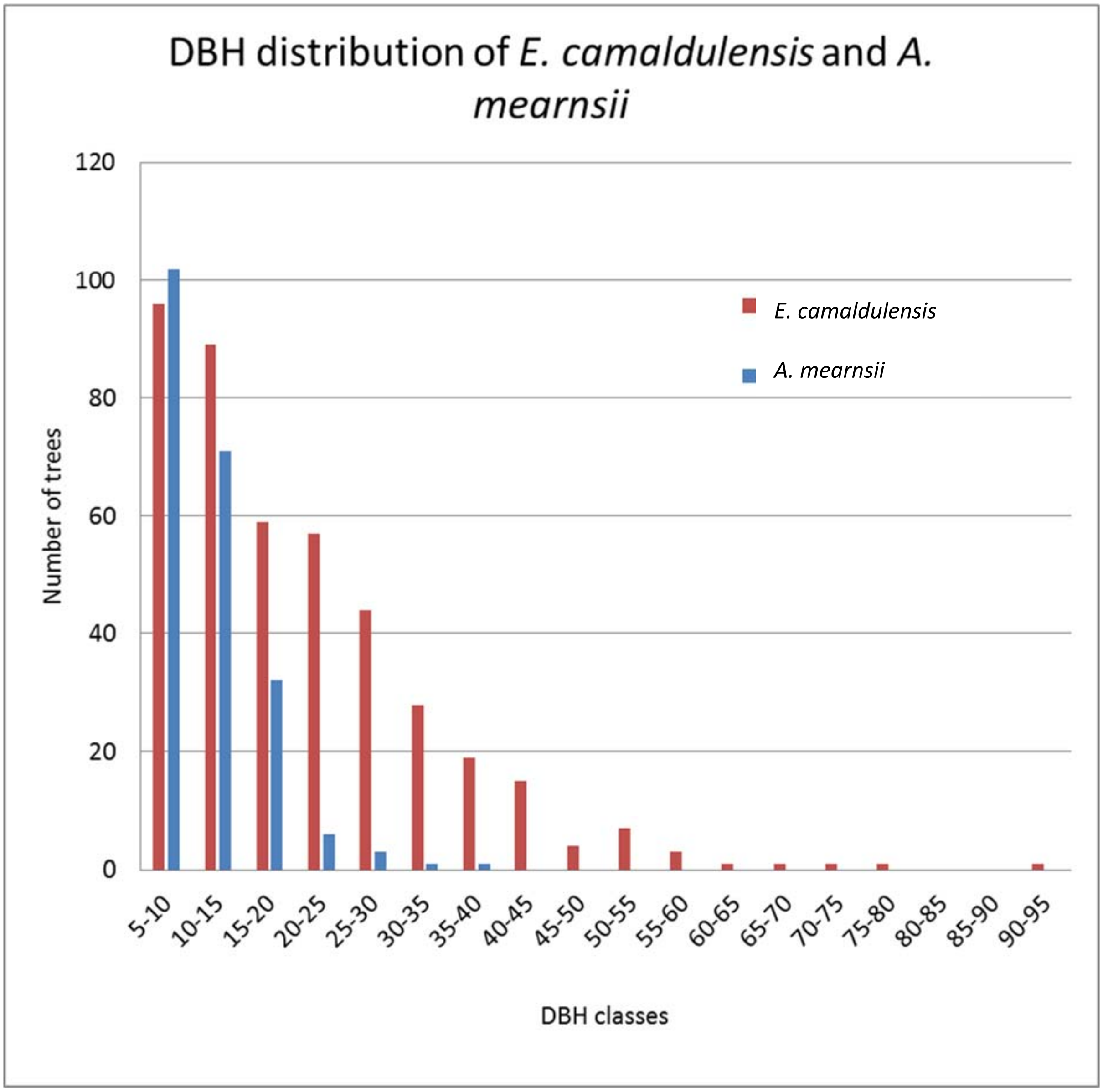


Figure 27: Histogram of diameter at breast height (DBH ≥ 7.5 cm) of trees measured on the study site. *E. camaldulensis* (orange) outnumbers *A. mearnsii* (blue) approximately 2:1.

4.2 Prediction of stand height

Table 13 below shows the regression height models used to estimate standing volume. Five different regression models were investigated (exponential, power, linear, logarithmic, polynomial) to best explain the relationship between DBH and height. The model coefficient of determination (R^2) value was used as the criterion for model selection (Table 13 and Table 14 and Figure 28). Two different models were used for the two species at the site, both explaining just over 60% of the variation.

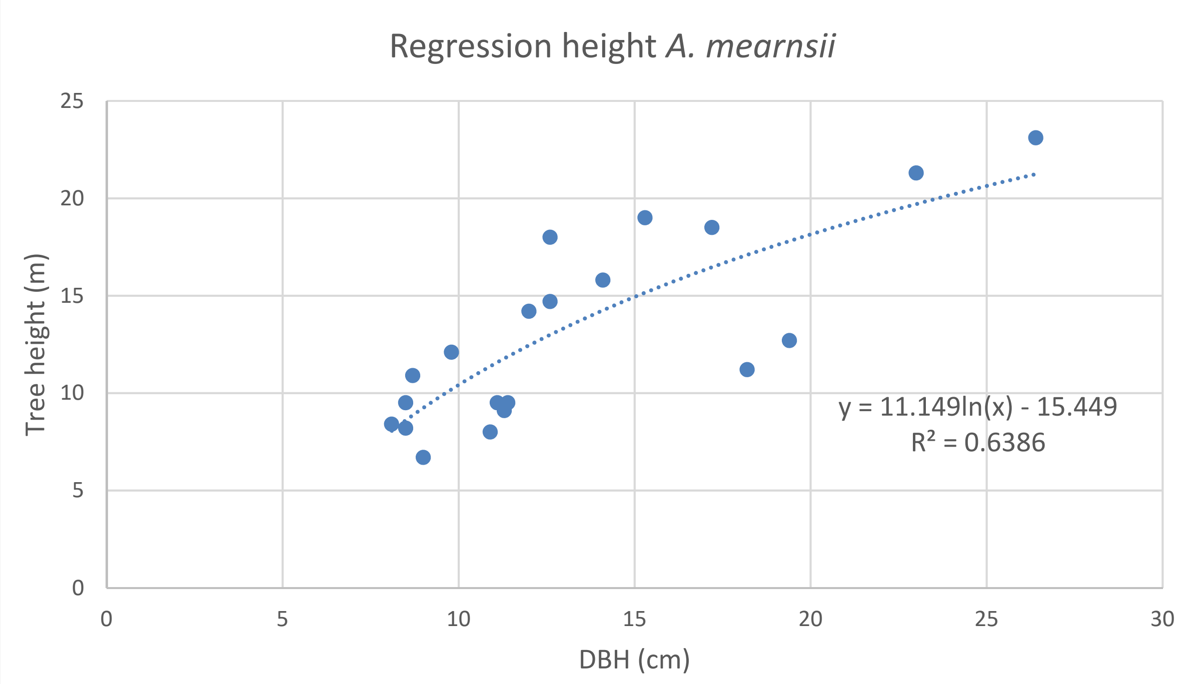
Table 13: Estimated models for height from DBH (given as x), R^2 values, mean DBH, and mean height for *Acacia mearnsii* and *Eucalyptus camaldulensis* on the study site.

	Species	
	A. mearnsii	*E. camaldulensis*
Regression height model	$y = 11.149\ln(x) - 15.449$	$y = 3.1083x^{0.5763}$
R^2	0.6386	0.603
Mean DBH (Dq cm)	11.77	23.57
Mean height (m)	10.89	17.31
Dominant height (m)	19.03	20.30

Table 14: Summary of various DBH-Height regression functions and R^2 values for *Acacia mearnsii* and *Eucalyptus camaldulensis* on the study site. The logarithmic function was chosen for *Acacia* and the power function for *Eucalyptus*

Regression height model type	*A. mearnsii*	R^2	*E. camaldulensis*	R^2
Linear	$y = 0{,}7568(x) + 2{,}7568$	0.6351	$y = 0{,}3651(x) + 10{,}792$	0.5366
Polynomial	$y = -0{,}0098(x)^2 + 1{,}0732(x) + 0{,}5161$	0.6381	$y = -0{,}0021(x)^2 + 0{,}5336(x) + 8{,}2504$	0.552
Exponential	$y = 5{,}8176e^{0{,}0545(x)}$	0.5898	$y = 11{,}758e^{0{,}0182(x)}$	0.4596
Logarithmic	$y = 11.149\ln(x) - 15.449$	0.6386	$y = 10{,}53\ln(x) - 12{,}614$	0.5827
Power	$y = 1{,}5052(x)^{0{,}822}$	0.617	$y = 3.1083(x)^{0.5763}$	0.603

There was a noticeable amount of variability in tree height across the DBH range of the sampled trees (Figure 28).



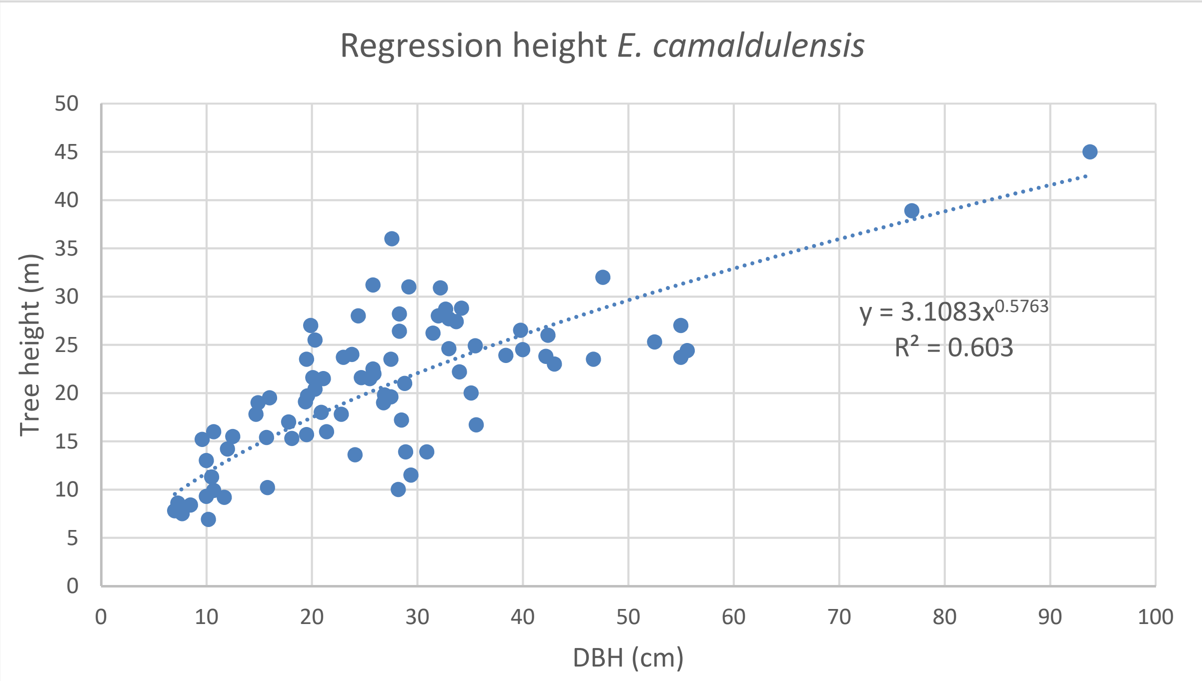


Figure 28: Scatterplots showing DBH-height relationship for *A. mearnsii* (top) and *Eucalyptus camaldulensis* (bottom) trees measured on the study site. The regression function showing the best coefficient of determination is shown.

4.3 Prediction of standing volume and stem form

Five diameter classes were used to classify DBH (in Table 15 below), with *A.mearnsii* showing fewer large diameter trees than *E. camaldulensis*.

Table 15: Mean number of trees per hectare per DBH class on the study site

	DBH classes				
Species	7.5 – 16 cm	16 – 26 cm	26 – 36 cm	36 – 46 cm	> 46 cm
	Mean number of trees/ha				
A. mearnsii	148	32	5	1	0
E. camaldulensis	164	133	76	32	22

Table 16 below lists the standing volume of trees (DBH ≥ 5 cm) measured on the study site. *Eucalyptus* trees outnumber the *Acacia* trees roughly 2:1. *Eucalyptus* represents 7:1 greater BA than *Acacia*, but in terms of volume, *Eucalyptus* represents nearly 13:1 greater volume than *Acacia*. This is due to the volume of the mean tree. Mean height and mean DBH are both considerably larger for *Eucalyptus* than for *Acacia* (Table 13) which explains the large difference in BA (DBH) and in volume (DBH and height). Simple calculations can be carried out to test the effect of changes in diameter on the area of a circle, and on cylinder volume if that circle is multiplied by height. Doubling the diameter of a circle quadruples it's area, while doubling the height of cylinder will simply double its volume. This seems to roughly explain these large differences in basal area and volume between the species. Mean DBH of *Eucalyptus* is more than twice that of *Acacia*, and the mean height of *Eucalyptus* is nearly double that of *Acacia*. Furthermore, *Eucalyptus* also has a greater ratio of large trees to small trees compared to *Acacia* (Table 15).

Table 16: Summary of context-setting standing volume (DBH ≥ 5 cm) calculated using Schumacher and Hall standing volume equation.

	Species	
	E. camaldulensis	*A. mearnsii*
Plot area (ha)	0.88	0.88
Stand area (ha)	10.66	10.66
Mean tree volume (m^3)	0.47718 (n=428)	0.06968 (n=216)
Standard Deviation (of mean tree volume)	0.89291	0.12635
Standard Error (of mean tree volume)	0.04316	0.00859
Stems per hectare (STPH)	486	245
Volume per hectare (m^3/ha)	231.74	17.1
Stand volume (m^3/10.66 ha)	2470.35	182.25

Table 17 below shows the mean stand volume per hectare (m^3/ha) for *A. mearnsii* and *E. camaldulensis* per DBH class for all trees (DBH ≥ 7.5 cm) over 22 sample plots measured in the inventory. These results are a continuation of Table 15 and Table 16 showing, for example, how no *A. mearnsii* trees were measured in the largest DBH class (DBH > 46 cm).

Table 17: Stand volume (Schumacher and Hall - Equation 1) per hectare (m^3/ha), per DBH class

	DBH classes				
Species	7.5 – 16 cm	16 – 26 cm	26 – 36 cm	36 – 46 cm	> 46 cm
	Stand volume per hectare (m^3/ha)				
A. mearnsii	7.633803	6.362159	2.311486	1.453131	0
E. camaldulensis	12.09171	39.20841	56.00316	45.59395	81.94

4.3.1 Estimated taper: Demaerschalk and Max and Burkhart

Table 18 below gives the baseline log volume (DBH ≥ 7.5 cm to upper stem diameter of 7.5 cm) over 22 plots on the study site. Equation 2 and Equation 3 (section 3.7) were used to calculate these values. Changes in log volume resulting from measurements of utilisable height (butt-log length/height at first major branching), and taper (upper stem diameter at height at first major branching), using the gator eyes laser calliper were made against these, the results of which are presented in section 4.4. In Table 18 below, mean log volume for *E. camaldulensis* as derived from the Schumacher and Hall standing volume function (Equation 1) is slightly lower than in Table 16 above (mean tree volume), but higher for *A. mearnsii* than in Table 16 above.

Table 18: Summary of species-specific taper functions (Equation 2 and Equation 3) used to define log length at upper-stem diameter of 7.5 cm (DBH ≥ 7.5 cm)

	Species	
	E. camaldulensis (Equation 3)	*A. mearnsii* (Equation 2)
Mean log volume (m^3)	0.445591 (n=382)	0.093091 (n=158)
Standard Deviation of mean log volume	0.67268	0.142475
Standard Error of mean log volume	0.0344417	0.011335
Volume per hectare (m^3/ha)	193.37	16.71
Stand volume (m^3/10.66 ha)	2061.32	178.13

4.4 Sub-sample: measurement of tree taper and form

The following sub-sections 4.4.1 - 4.4.6 deal with the sub-sample treatments. That is, estimates are made relying not only on DBH and height measurements, but also data from laser calliper, photogrammetry, and terrestrial LiDAR scans. As mentioned in section 3.5, height at first major branching, taper, and stem sweep were assessed with these treatments. Log length is directly related to height at first branching (if the tree is not leaning) which affects log volume.

Table 19 below is the result of the weighted sampling method (as described in Chapter 3) based on the study site's diameter (DBH) distribution for both *Eucalyptus camaldulensis* and *Acacia mearnsii* (including the trees initially measured for height). An R script was developed for this process.

Table 19: Tree selection for 'gator eyes' enumeration based on diameter (DBH) distribution data *E. camaldulensis* and *Acacia mearnsii* for study site ''Paarl farm'' (site type A).

Eucalyptus camaldulensis	
Diameter intervals (cm)	No. of trees per interval
5.10 – 13.97	19
13.97 – 22.84	24
22.84 – 31.71	26
31.71 – 40.58	14
40.58 – 49.45	4
> 49.45	7
Total	94
Acacia mearnsii	
Diameter intervals (cm)	No. of trees per interval
5.10 – 7.94	3
7.94 – 10.78	9
10.78 – 13.63	10
13.63 – 16.47	3
16.47 – 19.31	3
> 19.31	4
Total	32

4.4.1 Butt-log length/height reduction: Laser Calliper

Table 20 below shows utilisable sawlog volume calculated taking the height at first major branching into account (on average, for the mean tree per species), as measured using the laser eyes calliper (DBH ≥ 7.5 cm). This is compared with "basic" volumes as calculated using the species-specific taper functions (Equation 2 and Equation 3). The difference in control log volume compared to the reduced (both total and mean) is large showing the importance of major branching height in reducing sawlog volume.

Table 20: Utilisable sawlog volume reductions resulting from height at first major branching for the mean tree (per species) measured using the laser eyes calliper

	Acacia mearnsii	*Eucalyptus camaldulensis*
	Height at first major branching reduction	Height at first major branching reduction
Total control log volume (m^3)	3.1281 (n=29)	59.0669 (n=93)
Mean control log volume (m^3)	0.1079 (n=29)	0.63513 (n=93)
Standard deviation of mean log volume	0.1579	0.7672
Standard Error of mean log volume	0.0293	0.0796
Total reduced log volume (m^3)	2.1778 (n=29)	41.4120 (n=93)
Mean log volume (m^3)	0.0751 (n=29)	0.4453 (n=93)
Standard deviation of mean log volume	0.0873	0.5313
Standard Error of mean log volume	0.0162	0.0551

Tree lean was prominent on the study site. Measuring leaning trees for height has the effect of lowering mean tree height when considering DBH-height regression models created to estimate tree height for the entire stand/study site. For estimates of standing volume, leaning trees will underestimate total standing volume (Clark, et al., 2000). While the extent and effect of tree lean on standing volume is not investigated in this study it certainly affects stem and wood quality by increasing the percentage of reaction wood in the stem (Wilson & Gartner, 1996).

4.4.2 Butt-log length/height reduction: issues with Photogrammetry

An important outcome of this study was finding that photogrammetry underestimated utilisable sawlog length (Table 21 – when compared to the same tree measured with the laser calliper). This was due mainly to obstructions from low-hanging branches (and foliage) which affected the visible utilisable sawlog height. Figure 29 shows how low-hanging branches can obstruct visibility of the stem. This means that the data were not useful for the estimates in the analyses in the present study.

Table 21: Comparison of height at first major branching measured on the same subject trees using the photogrammetry system and laser calliper system, but with photogrammetry showing an underestimation in comparison

Tree ID no.	Species	Photogrammetry height at first branching (m)	Laser calliper height at first branching (m)
18	*E. camaldulensis*	7.8	8.6
146	*E. camaldulensis*	4.4	5
535	*E. camaldulensis*	4.4	8.7
538	*E. camaldulensis*	4	8.4
624	*E. camaldulensis*	4.9	8

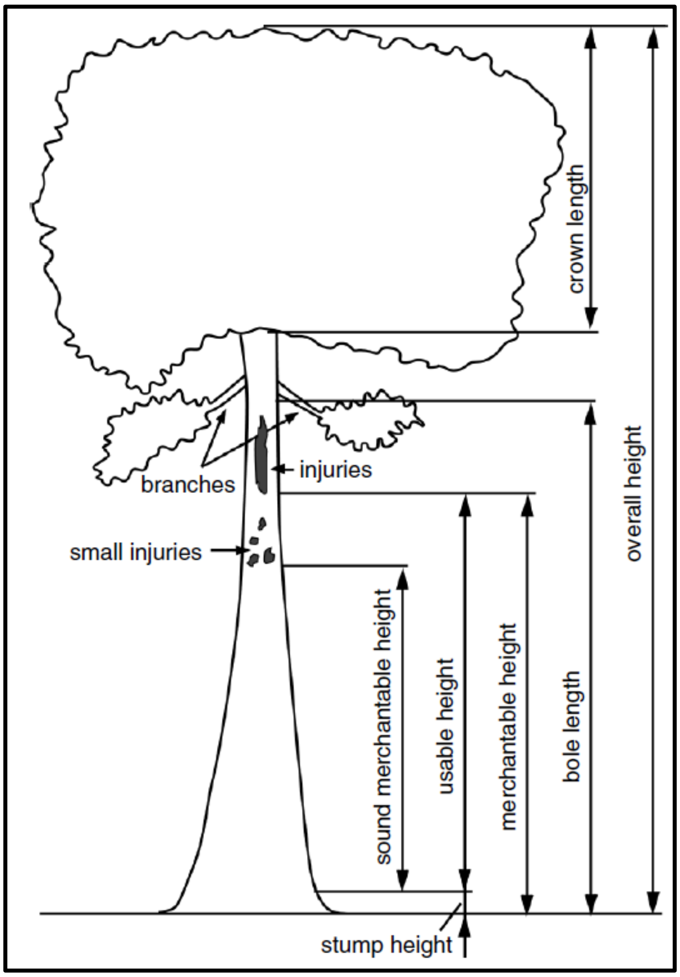


Figure 29: Diagram showing how low-hanging branches obstruct photogrammetric reconstruction and recording of tree height at major branching for a realistic estimate of utilisable sawlog length (bole length) (Köhl, et al., 2006).

Figure 30 below shows a good example of the effect of branching that was typical of the reconstructions. Notice how towards the top of the stems considerable distortion in the reconstruction has occurred due to the presence of low-hanging branches and foliage which have subsequently been removed leaving the reconstructed stems with an underestimated first branching height compared to in-field visual assessments of the same tree.

Figure 30: Double-leader tree stem photogrammetrically reconstructed in Agisoft Photoscan, but now open in CloudCompare. The tops of the reconstructed stems are inadequately reconstructed due to the presence of low-hanging branches and foliage.

To extract more accurate sawlog length values the photography method used would have to be improved by taking more photographs closer to the subject tree. More specifically, photos which included more of the upper stem which is only visible behind the obstructing low-hanging branches and leaves.

Hindrance to full stem reconstruction can also be attributed to trouble with photo registration. Difficulty was encountered when registering multiple photos to each other in order to extract accurate upper diameters of bigger trees (Liang, et al., 2014; Clark, et al., 2000). Without adequate correction through improvements of the photography system used, the photogrammetry will continue to deliver an underestimation of log volume, but this problem is not completely insurmountable. As a result, photogrammetry was utilised, but later abandoned. While photogrammetry systems using hand-held cameras to model tree stems and extract tree-level DBH estimates have been shown to be deliver results acceptable for practical applications, trouble is still encountered in mapping small trees and complex forest stands (Liang, et al., 2014). The use of photogrammetry in future NRM inventories to measure utilisable sawlog length (or even just DBH), as described in this study is considered a research tool only and would not make sense to use for future NRM inventories. The time-consuming process of extracting tree-level data from point cloud data in comparison to conventional diameter tape measurements illustrates this point further.

4.4.3 Constant-form taper modification: Laser Calliper

Table 22 below shows utilisable sawlog volume having taken into account taper as derived from upper stem diameter measured at height at first major branching for the mean tree (per species). These log volumes calculated from modifications of taper are compared with volumes calculated using the species-specific taper functions (Equation 2 and Equation 3) which were then reduced for height at first major branching (Table 20). The difference in control log volume compared to the modified (both total and mean) is not large, although in this instance the volume resulting from modifications of taper for the same length of log is higher (Table 22), different to the effect of first major branching height on log volume which reduced the control log volume considerably (Table 20). Taper influences utilisable sawlog volume, but only minimally in comparison to height at first major branching.

As a side note, such taper models (Equation 2 and Equation 3) are developed from many destructive measurements of diameter across the height range of subject trees. These models are developed from a broad range of trees growing under various conditions and can then be applied universally to trees of the same species. With this, error is therefore introduced in their application, but the extent of which is not fully known without testing specific cases against the results of the models. This is what was done in this study, to some extent, but the error was not tested to make statistical inferences about which is better to use.

Table 22: Utilisable sawlog volume differences resulting from log taper measured using the gator eyes laser calliper compared to sawlog volume resulting from species-specific taper equations (Equation 2 and Equation 3). Height and stem diameter at first major branching height was used to define log volume (m^3).

	Acacia mearnsii	*Eucalyptus camaldulensis*
	Taper	Taper
Total control log volume (m^3)	2.1778 (n=29)	41.41197 (n=93)
Mean control log volume (m^3)	0.0751 (n=29)	0.4453 (n=93)
Standard deviation of log volume	0.0873	0.5313
Standard Error of mean log volume	0.0162	0.0551
Total modified log volume (m^3)	2.2776 (n=29)	42.5063 (n=93)
Mean log volume (m^3)	0.0785 (n=29)	0.4571 (n=93)
Standard deviation of mean log volume	0.0871	0.5516
Standard Error of mean log volume	0.0163	0.0572

Measurements of stem taper did not influence recoverable sawlog volume (for the same log length) as much as height at first major branching did. The differences in sawlog volume resulting from measurements of upper stem diameter (to derive taper for volume calculations), compared to species-specific taper model outputs for the same upper stem diameter position, were not large enough to justify the time-consuming measurements of upper stem diameter using the gator eyes laser calliper. This is to say, for example, if future NRM studies investigating stem form required upper stem diameter measurements, but only had tree height data at various points up the stem, then relevant literature could be reviewed and suitable species-specific taper functions could be used to derive acceptable results. Although, both Demaerschalk's function and the Max and Burkhart function delivered lower log volumes compared to measurements made using the gator eyes laser calliper, from a planning perspective it would make sense to accept more conservative estimates, especially when the differences are not major, as in this study. The underlying benefits of choosing a model over in-field measurement is the time and therefore money saving because these models rely on DBH as input which in comparison is easier to collect than upper stem diameter measurements.

4.4.4 Constant-form taper modification: Laser Calliper upper stem diameter measurements

Concerning distance of laser calliper measurements to the point on the stem in this study, upper stem diameter was not measured further than 12 m from the measurement point on the stem. Logs longer than 12 m (i.e. trees with branching higher than 12 m) were, however, measured in this study, but the distance was minimised to below 12 m by standing directly beneath the measurement point on the stem and extending the arms to above the head. This method, taking the height of the practitioner and their arm length into account, ensured that the measurement distance was minimised to deliver an accurate upper stem diameter measurement. Furthermore, by choosing to stand approximately beneath the measurement point of the upper stem while maintaining a complete view of the cross-section of the stem ensured the shortest possible travel path of the laser to the measurement point.

4.4.5 Stem sweep: extraction of estimates

Using the 12 sub-sampled trees isolated in TLS scans of two sample plots on the study site, volume calculations were undertaken also taking sweep into account. Due to the presence of undergrowth, not all scanned trees could be isolated. Once a tree was isolated, noise distortion (branching) was removed, the log isolated, and the remaining points representing the log processed with the developed R script to extract an estimate of sweep over two planes. Figure 31 below shows this manual process from isolated tree to isolated log – notice the ground-level, stem, and upper branches. The stem is the most discernible section of the tree and is used in further analysis. Figure 31, a *Eucalyptus* example, was chosen because this log illustrates the greatest effect of sweep of all the logs processed. The white arrows point out three regions of sweep on the log. Taper is also illustrated by the decrease in diameter up the stem. Figure 32 shows a 3-dimensional visualisation of the same log (length > 8 m), with the same sweep regions illustrated, only this time more pronounced due to reduced height scaling. The process is time-consuming due to the individual attention each isolated tree/log requires. Noise (points) must be removed which could otherwise distort diameter and sweep measurements the R script delivers. Without removing finely detailed noise distortion this stem sweep extraction method would not work properly. Logs from across the diameter and length range, and from both species were processed with the script.

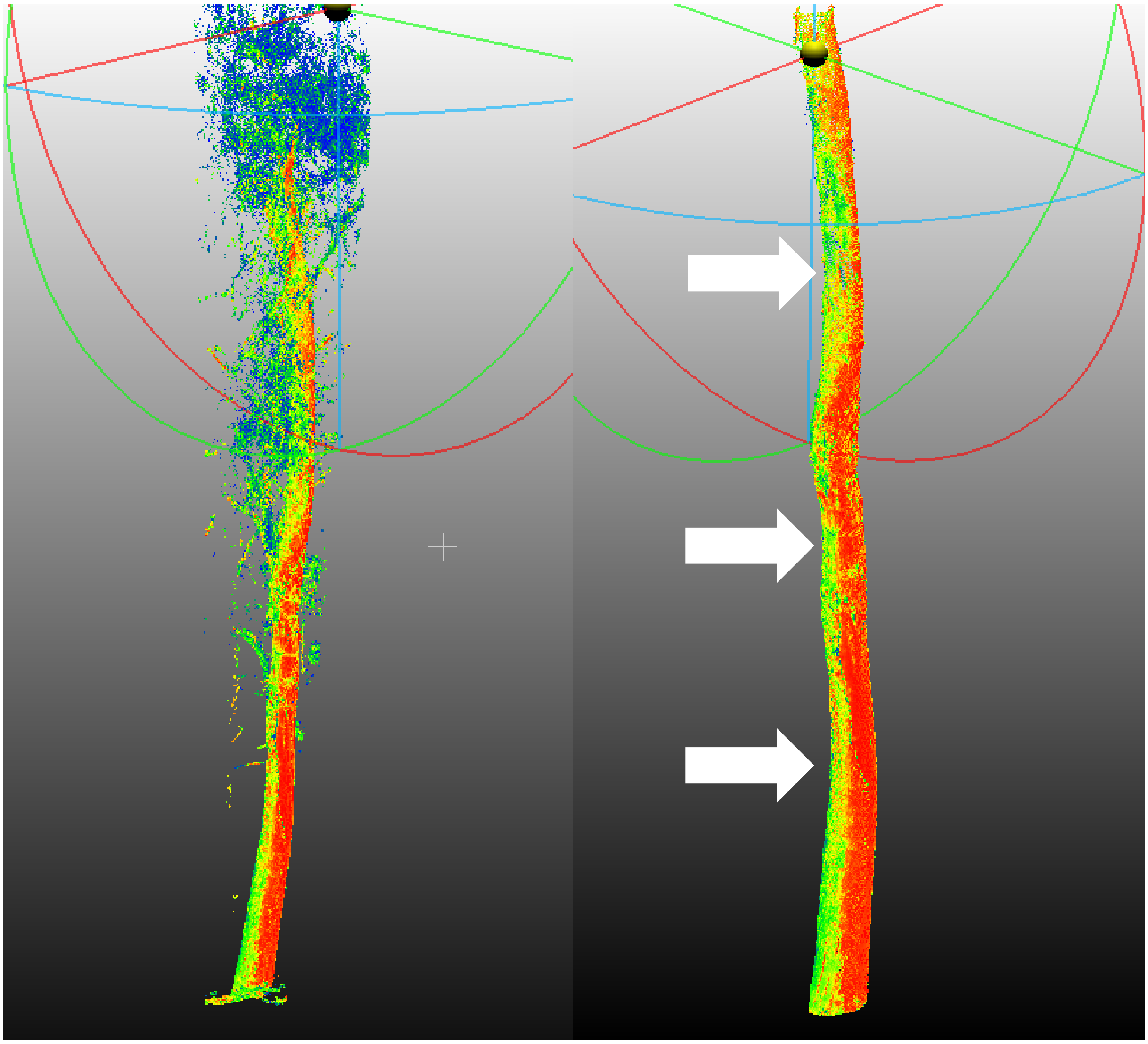


Figure 31: Left - tree isolated from a LiDAR scan. Right - point cloud data of a stem section isolated from the same tree scanned using a high-resolution LiDAR scanner on the study site.

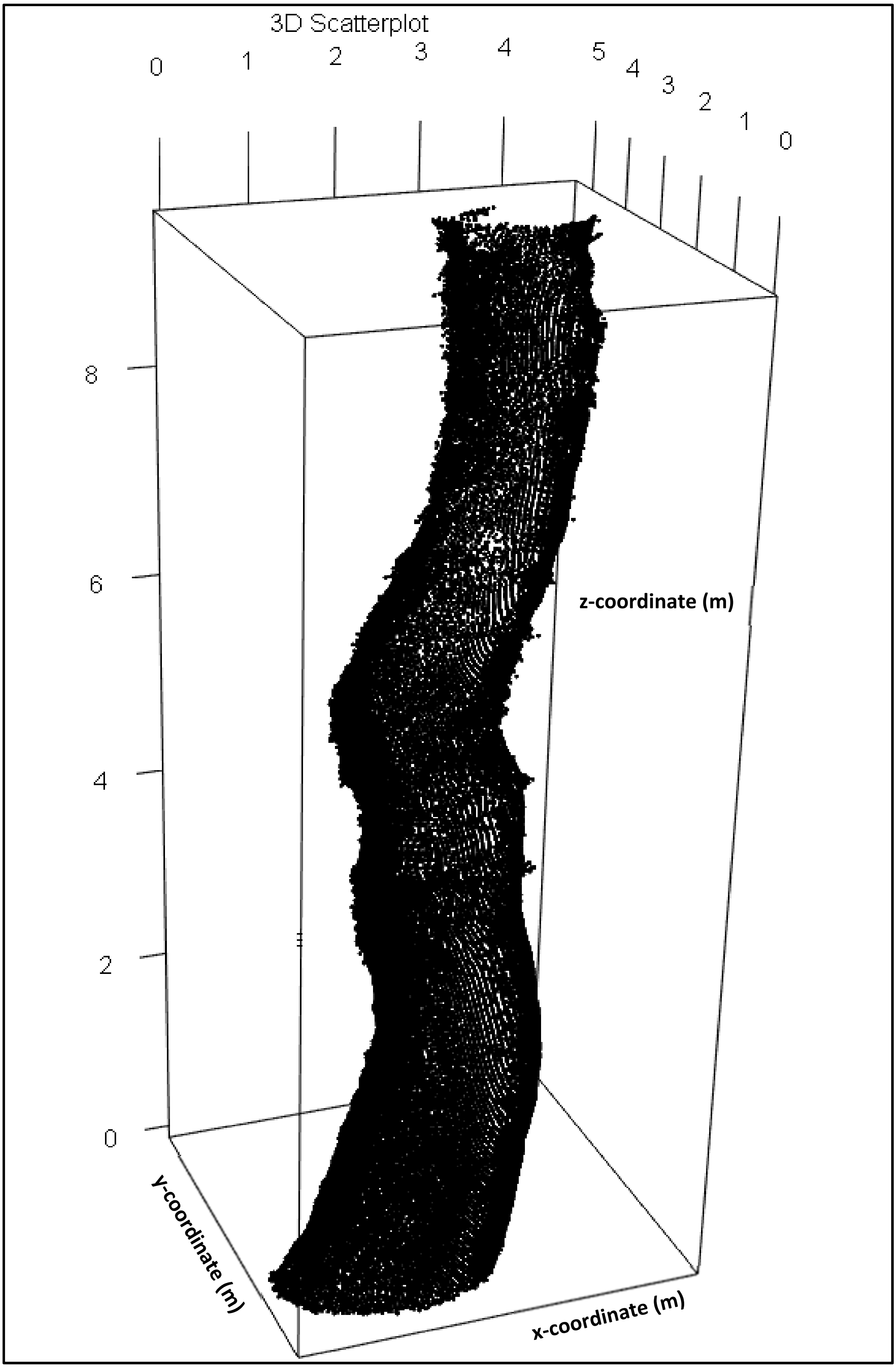


Figure 32: 3-dimensional scatter plot used to visualise log profile. This log is the same as shown in Figure 25 and illustrates log length (>8 m)

Table 23 below presents log sweep estimates of the sub-sample of trees scanned using TLS. Logs were isolated and then processed with the R script to give log sweep in two planes. None of the logs showed sweep relative to only one plane meaning that overall sweep would have to be calculated over both planes for input into sawing simulations. On average, *Eucalyptus* logs were longer than *Acacia* logs, with sweep also more pronounced for the longer logs. One log showed sweep more than 100 mm (log ID 23 – the same log used to illustrate sweep in Figure 23, Figure 31 and Figure 32.

Table 23: Log sweep values from trees scanned using TLS on the study site and processed using a R script

log ID no.	Species	Small-end diameter (cm)	Big-end diameter (cm)	Length (m)	Taper (mm/m)	Max sweep x-plane (mm)	Max sweep y-plane (mm)
6	*E. camaldulensis*	29.1	40.3	6.4	17	47	49
7	*E. camaldulensis*	32.03	44.85	6.5	19	94	80
23	*E. camaldulensis*	23.66	33.42	8.3	12	128	97
27	*E. camaldulensis*	14.8	17.2	2.5	8	24	21
34	*E. camaldulensis*	28.5	37.9	5.8	16	74	35
608	*A. mearnsii*	8.78	11.27	3.3	8	37	66
609	*A. mearnsii*	13.33	19.51	3.7	17	37	85
620	*A. mearnsii*	7.19	9.42	3.9	6	32	63
625	*A. mearnsii*	8.1	8.42	1.1	2	24	36
660	*E. camaldulensis*	31	51.86	8.5	25	53	53
661	*A. mearnsii*	6.89	8	2.4	3	36	24
902	*E. camaldulensis*	17.47	22.26	3.6	13	63	57

4.4.6 Stem sweep: undergrowth and branching obstructions in LIDAR data

Factors contributing most to the low number of trees isolated in the registered LiDAR scans were (1) the low number of sample plots scanned, and (2) obstruction from other trees and undergrowth. After numerous attempts to isolate trees and extract tree-level data, it became clear that dense undergrowth along with the plot scan layout impeded the scanner from capturing complete stem detail (Watt & Donoghue, 2007; Bienert, et al., 2007). The 5-scan layout used maked it difficult to isolate complete trees from the outer reaches of the sample plot due to the plot radius (11.28 m) in comparison to the 5 m movement in each cardinal direction. The presence of other trees obstructing the scanner also played a role in not scanning and reconstructing stems completely. The developed R script also required point cloud data representing a complete stem, or at least more than 270 degrees of the stem cross section. As with the photogrammetry treatment, low-hanging branches, foliage and undergrowth were also to blame for obstructing scans making it difficult to extract complete stems for processing with the R script.

The Z+F LaserControl proprietary software package (Zoller + Frolich, 2017) was used to register high-resolution LiDAR scans. 5 scans per plot were taken and a manual process of registration used to deliver point cloud data of all 5 scans in a unified coordinate system. The trouble with manual point cloud registration is that individual reference points representing similar objects in multiple scans must be sought out and aligned to one another. Without the help of automated registration algorithms and artificial reference objects placed throughout the scanned sample plot, this process can be time-consuming as similar irregularities (e.g. defect on stem) must be found and used as reference objects (Dassot, et al., 2011).

Once scan registration was complete, CloudCompare, the open source software used to process point cloud data attained from the high-resolution LiDAR machine was used for manual isolation of trees and removal of noise from isolated stems. The process is however time-consuming, as is using CloudCompare for registration (Rajendra, et al., 2014).

In terms of feasibility for use in future NRM inventories, pursuing LiDAR as used in this study as a standard inventory method is ambitious, so for now it too can be considered only a research tool. LiDAR systems are expensive to purchase and require trained technicians to process and extract tree-level data from 3-dimensional point clouds, not forgetting the cost of computing power and proprietary software required to streamline the process. However, if NRM would like to pursue TLS inventories as a permanent inventory method then an alternative could be to out-source the process on a contract basis. Using a combination of aerial and terrestrial LiDAR would deliver the most useful results (Lindberg, et al., 2012).

4.5 Simsaw 6 simulations: Recovery volumes

The following tables present the mean sawn product volume recovery percentages for the mean control log and modified log per species from Simsaw 6 simulations. The input logs for the simulations are the same as the logs in Table 20, Table 22, and Table 23 with recovery values presented at each incremental modification step (first major branching height – Table 24, taper – Table 25, and sweep – Table 26). Total and mean recovery volume (m^3) reflects the total and mean log volume (m^3) input used in the simulations. The recovery volume percentages presented in the following three sections refers to dry product volume. The full Simsaw 6 report files are included in section Appendix: Simsaw 6 simulations.

4.5.1 Butt-log length/height reduction: Laser Calliper

From Table 24 below it is clear that including more detailed information about height at first major branching lowered the mean input volume of logs (modified) compared to assumed volumes from DBH and height (same number of logs, n = 29). Volume recovery percentage value is shown, but should not be interpreted without considering the multitude of factors affecting volume recovery percentage in a sawmill environment. Dimensions of sawn product types (Table 3) were defined together with a standard sawing pattern for each log class across simulations.

Table 24: Recovery volume (and percentages) per species for control logs (upper diameter of 7.5 cm) vs. logs shortened to height at first major branching height

	Acacia mearnsii	*Eucalyptus camaldulensis*
	Reduction due to height at first major branching	Reduction due to height at first major branching
Input control log volume (m^3)	3.1281 (n=29)	59.0669 (n=93)
Total control recovery volume (m^3)	0.9379 (n=29)	28.6090 (n=93)
Mean control recovery volume (m^3)	0.0323 (n=29)	0.3077 (n=93)
Volume recovery (%)	29.98	48.43
Input reduced log volume (m^3)	2.1778 (n=29)	41.4120 (n=93)
Total reduced log recovery volume (m^3)	0.6207 (n=29)	20.7403 (n=93)
Mean reduced log recovery volume (m^3)	0.0751 (n=29)	0.2230 (n=93)
Volume recovery (%)	28.5	50.08

The volume recovery percentage for *Eucalyptus* given above in Table 24 is higher for the reduced logs than for the control logs, meaning that the log dimensions used as input were more favourable considering the dimensions of the sawn products. The opposite is observed in the case of *Acacia.* The volume recovery percentage value does not necessarily reflect the volume of the total and mean logs used as input to the simulations. What it means is that more of the input logs' volume could be converted into sawn product, (i.e. sawn product to log volume ratio).

4.5.2 Constant-form taper modification: Laser Calliper

Table 25 below shows mean volume recovery of logs having taken into account taper as derived from upper stem diameter measured at height at first major branching for the mean tree (per species). These log taper modifications are compared with volumes calculated using the species-specific taper functions (Equation 2 and Equation 3) which were then reduced taking height at first major branching into account and run through Simsaw 6. The difference in control recovery volume compared to the modified recovery volume (both total and mean) is not large, and this instance for *Acacia* the volume recovery resulting from modifications of taper for the same length of log follows the opposite trend as in the reduction of height (Table 24). *Acacia* now reported a higher volume recovery for the modified logs compared to the control (Table 25).

For both species the mean input log modified for taper is larger than the control log due to the increased input log volume (Table 25 – *Acacia*: 2.2776 vs. 2.1778; *Eucalyptus*: 42.5063 vs. 41.4120). The volume recovery percentage values are shown and mean that for *Acacia* more of the modified logs' volume could be converted into sawn product than the control while *Eucalyptus* showed roughly the same percentage of sawn product volume recovery.

Table 25: Recovery volume (and percentages) per species for control logs vs. modified logs resulting from log taper measured using the gator eyes laser calliper. Height and stem diameter at first major branching was used to define log volume (m^3)

	Acacia mearnsii	*Eucalyptus camaldulensis*
	Taper	Taper
Input control log volume (m^3)	2.1778 (n=29)	41.4120 (n=93)
Total control recovery volume (m^3)	0.6207 (n=29)	20.7403 (n=93)
Mean control recovery volume (m^3)	0.0751 (n=29)	0.2230 (n=93)
Volume recovery (%)	28.5	50.08
Input modified log volume (m^3)	2.2776 (n=29)	42.5063 (n=93)
Total modified log recovery volume (m^3)	0.6755 (n=29)	21.2840 (n=93)
Mean modified log recovery volume (m^3)	0.0233 (n=29)	0.2287 (n=93)
Volume recovery (%)	29.66	50.07

4.5.3 Stem sweep

Log sweep was calculated and used as input into Simsaw 6. Sweep values for the x-plane and y-plane listed in Table 23 (above) were used to calculate average log sweep. Table 26 below lists total and mean recovery volumes for the same logs tested with sweep, and without sweep. Because Simsaw 6 can only process logs to a maximum sweep of 40 mm (i.e. sweep values ≤ 40 mm). All but three of the logs exceeded this maximum allowable sweep value, therefore reverting their input sweep values to the default maximum of 40 mm. The results show that for *Eucalyptus* volume recovery does indeed decrease (considerably, 20.14%) when sweep is introduced. This can most likely be attributed to logs longer than industry standards (Table 23: log ID no. 23 and 660, longer than 8 m). This was an extreme case illustrating the effect of stem sweep on volume recovery. In the case of *Acacia*, a minor increase was noticed when sweep was introduced. This can be attributed to the low number of logs tested, the small dimensions of the logs and their orientation in the saw. The offset orientation in the shorter, narrower *Acacia* logs most likely improved the software's capability of sawn product from the logs. If the software could accept logs with sweep greater than 40 mm, the effect of log sweep on volume recovery percentage could be illustrated better for *Acacia* – increase in log sweep will see a decrease in recovery volume percentage. Values for taper and small end-diameter were also taken from the TLS data listed in Table 23 above.

Table 26: Total and mean recovery volume for logs with and without sweep measured in the TLS treatment on the study site

	Acacia mearnsii	*Eucalyptus camaldulensis*
Total log volume without sweep (m^3)	0.1435 (n=5)	3.8318
Mean log volume without sweep (m^3)	0.028691 (n=5)	0.54740 (n=7)
Total recovery volume without sweep (m^3)	0.0317 (n=5)	2.0929 (n=7)
Mean recovery volume without sweep (m^3)	0.00634 (n=5)	0.2990 (n=7)
Volume recovery (%)	22.08	54.62
Total log volume with sweep (m^3)	0.1435	3.8318
Mean log volume with sweep (m^3)	0.0287 (n=5)	0.54740 (n=7)
Total recovery volume with sweep (m^3)	0.0350	1.3213
Mean recovery volume with sweep (m^3)	0.0070 (n=5)	0.1888 (n=7)
Volume recovery (%)	24.37	34.48
Volume recovery difference (%)	+2.29	-20.14

The TLS system only presented sawlog sweep results for use in the study, but showed that sweep should be minimised through bucking to achieve the highest possible sawn product volume recovery percentage.

4.6 Sawlog Volume Correction Factor (SVCF)

Table 27 and Table 28 below present the results of the SVCF per hectare (m^3/ha), per species over five diameter classes. In each table, in the third row from the bottom, a percentage of loss is presented which shows the expected losses in utilisable sawlog volume per diameter class which can be expected when taking height at first major branching and taper into consideration. In the smallest DBH class of *A. mearnsii* an increase in volume is noticed, but in the larger diameter classes (26 – 36 cm), a loss as high as 50% can be noticed. The losses are not as pronounced for *E. camaldulensis* with a gradual increase in loss developing over the diameter classes. For *Acacia*, the highest loss appears in the middle diameter class (26 – 36 cm). For *Eucalyptus*, highest loss appears in the largest diameter class (> 46 cm), at roughly 30%. In the second row from the bottom a mean percentage of volume loss per hectare is also presented. In the bottom row, a total sawlog volume per hectare (m^3/ha) over all diameter classes is presented. These values were calculated against the initial standing volume calculated using the Schumacher and Hall function (Schumacher & Hall, 1933) for each species (Equation 1), taking the treatment data into account and is the result of the SVCF.

The results show that from measuring DBH and height (and stem count per hectare), a standing volume can be estimated, but to ascertain a more realistic estimate of the available sawlog volume the study site has to offer, the initial standing volume has to be reduced considerably taking height at first major branching and taper into consideration.

Table 27: ***Acacia mearnsii*** **mean sawlog volume per hectare (m³/ha) per diameter class and the losses attributed to reductions in sawlog volume froheight at first major branching and taper.**

A. mearnsii	DBH classes (cm)				
Treatment	7.5 – 16	16 – 26	26 – 36	36 – 46	> 46
	Mean sawlog volume per hectare (m^3/ha)				
Schumacher & Hall	7.6338	6.3622	2.3115	1.4531	7.6338
Control	5.9968	6.7342	2.9723	0	0
Height at first major branching reduction	5.7372	4.5100	1.5506	0	0
Taper modification	6.1801	4.8319	1.5102	0	0
Total Control volume loss (%)	+3.06	-28.25	-50.81	0	0
Mean control volume loss (%)	-25.33				
Total sawlog volume (m^3/ha - all diameter classes)	11.73				

Table 28: ***Eucalyptus camaldulensis*** **mean sawlog volume per hectare (m³/ha) per diameter class correction factor.**

E. camaldulensis	DBH classes (cm)				
Treatment	7.5 – 16	16 – 26	26 – 36	36 – 46	> 46
	Mean sawlog volume per hectare (m^3/ha)				
Schumacher & Hall	12.0917	39.2084	56.0032	45.5940	81.9400
Control	8.0958	36.6572	50.5315	42.7824	56.2460
Height at first major branching reduction	6.8163	28.0574	35.6528	30.5219	37.500
Taper modification	7.3237	30.3078	36.9288	29.2853	38.2920
Total Control volume loss (%)	-9.54	-17.32	-26.92	-31.55	-31.92
Mean volume loss (%)	-23.54				
Total sawlog volume (m^3/ha - all diameter classes)	144.69				

Of the inventory instruments tested, the laser calliper demonstrated accuracy in measuring upper stem diameter. Skovsgaard, et al. (1998), tested two commercial laser dendrometers against alternative instruments. The accuracy and precision of the remote diameter measurement functionality of the Laser Technology Criterion 400 was tested. It was found to overestimate the diameter by maximum 5% (hand-held) compared with a calliper measurement made on the same stem. This translates to the ± 5 cm DBH claimed accuracy by the manufacturer. While the instrument delivered precise measurements, users should recalibrate the instrument as frequently as possible to maintain accuracy as systematic bias is found in measurements. Emphasis is also placed on the importance of matching the instrument to the accuracy needs of the inventory. Considering these findings, such an expensive instrument as the Criterion 400 was deemed unsuitable for the conditions of this and future NRM inventory studies.

4.6.1 Utilisable sawlog volume and bucking bias in Simsaw 6

The results show that when considering utilisable sawlog volume, estimates of initial standing volume derived through measurements of DBH, height, and stem count per hectare are reduced through progressively more detailed measurements of stem form. These estimates of utilisable sawlog volume should be considered when determining the end-use of biomass cleared from NRM sites. The underlying finding of the study is that the riparian AIF type the study is concerned with will deliver a lower percentage of lumber (compared to total above-ground biomass) than that of a commercial plantation forest (Stafford & Blignaut, 2017).

With regard to recovery volume percentage of sawn products from Simsaw 6 simulations, some of the simulation runs saw a recovery volume percentage less than 30%, while others saw recoveries of greater than 50%. This has to do with the limited product options the simulations were sawing for. The products (used in manufacturing of school desks) represent only one sector of the spectrum of potential products the VAI programme currently manufactures. If smaller dimensional sawn products (e.g. component pieces used in finger jointing applications) were added to this product mix along with the component boards for school desks, the volume recovery percentages would improve for the simulations which reported low recoveries.

A factor which also influenced the volume recovery percentage values of sawing simulations is that Simsaw 6 cannot process logs longer than 10 m in length. This meant these logs were pre-bucked to a maximum length of 10 m for input into Simsaw 6. Taper values were used to define the small-end diameter of the remaining log length. This method circumvented any changes in actual log volume input into Simsaw 6, however, bucking (log length) affects the recovery volume percentage of sawn products (boards), and in this study the sawn products were few with large dimensional differences (Steele, 1984).

4.6.2 Demaerschalk's function in stem diameter measurements

For *Acacia mearnsii* on the study site, especially in the smallest diameter class (Table 27: 7.5 cm – 16 cm), Demaerschalk's function (Equation 2) overestimated the height at which 7.5 cm on the stem is found. This increased taper values in comparison to those measured using the laser calliper. Even though the average log lengths from Demaerschalk's function were longer, taper measured at a height of first branching using the laser calliper to an upper diameter of minimum 7.5 cm was not as high (i.e. logs showed less taper) and therefore increased the average log volume for the smallest diameter class. This suggests that Demaerschalk's function predicted a point at upper stem diameter of 7.5 cm very close to where height and diameter at first branching was measured using the laser calliper. This is found in the slight increase in log volume (+3.06 % in the SVCF - Table 27) defined for the smallest diameter class (7.5 cm – 16 cm), contrary to what was expected.

In short, the position at which Demaerschalk's function predicted upper diameter of 7.5 cm and the position at which the laser calliper measured first branching with upper diameter and height must have been very close to each other, but the logs (trees) measured using the laser calliper have less taper increasing the total and therefore mean tree volume in the smallest diameter class (Table 27: 7.5 cm – 16 cm).

4.7 Sampling and Precision

4.7.1 Analysis

The reason for testing the efficiency of the inventory study was to be able to develop recommendations towards cost-effective solutions for future NRM inventories of AIFs similar to the study site. For example, to simplify this complex aspect of NRM's clearing operations would be to use a simple sampling design requiring less field inventory crew, and the inventory itself could be carried out by harvesting contractors just before harvesting (pre-harvest inventory).

Plots exhibited broad variation in the number of trees per standard unit area. In one case, plot 6, only one tree occurred in comparison to plot 15 where more than 60 individual trees were measured. Figure 33 below shows the variation in the number of trees measured in each of the 22 sample plots. This is indicative of the patchy distribution of trees throughout the study site.

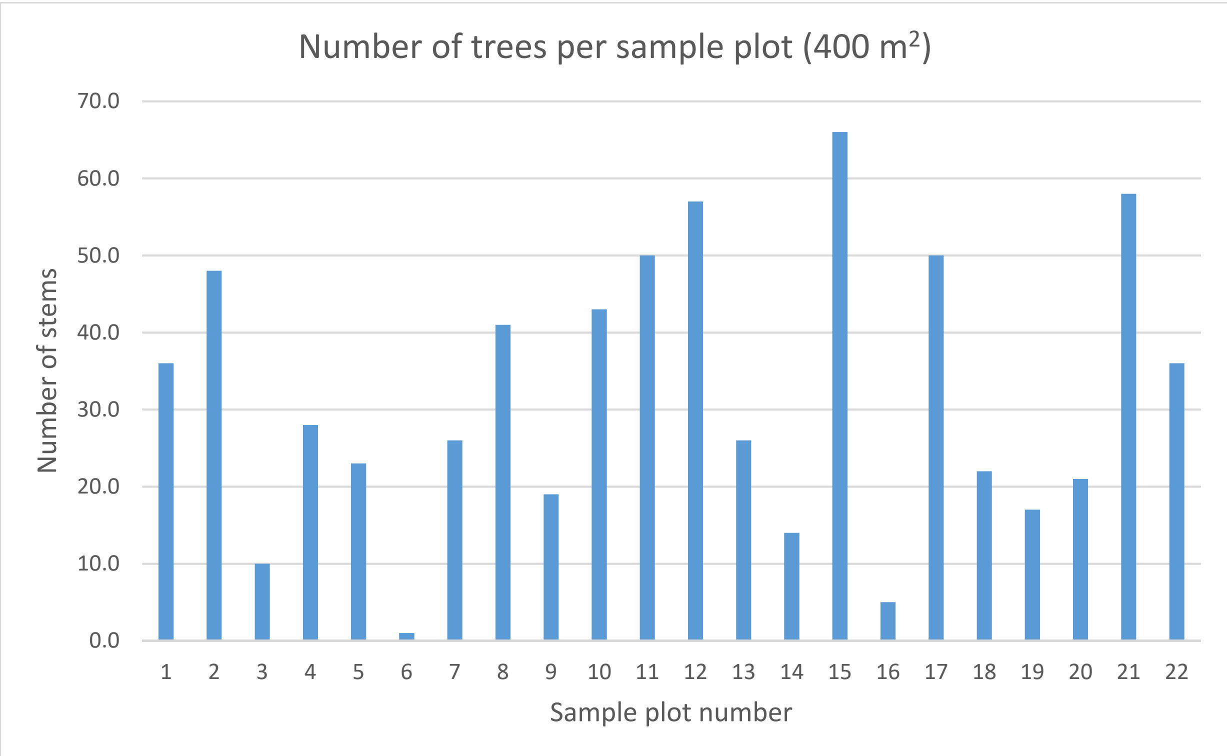


Figure 33: Bar graph of the number of trees per sample plot on the study site

Estimates of the relative standard error increased with a reduction of plot size (400 m^2, 300 m^2, 200 m^2, and 100 m^2) and decreased with an increase in hypothetical plot number of sample plots (Figure 34, Figure 35, and Table 29).

Given an estimate of standard deviation from the sample that was taken, the analysis showed 35 sample plots of 300 m^2 in size would be needed to achieve a precision level of less than 10% for the estimate of population volume 32 sample plots would yield a similar level of precision (Figure 35). In the case of BA, on the other hand, the population estimate would be within the acceptable limit with a smaller number of plots. Only about 26 plots of 400 m^2 would be needed. For BA the 10% threshold is achieved for the first time between 25 and 26 plots and is represented by a red line (Figure 34).

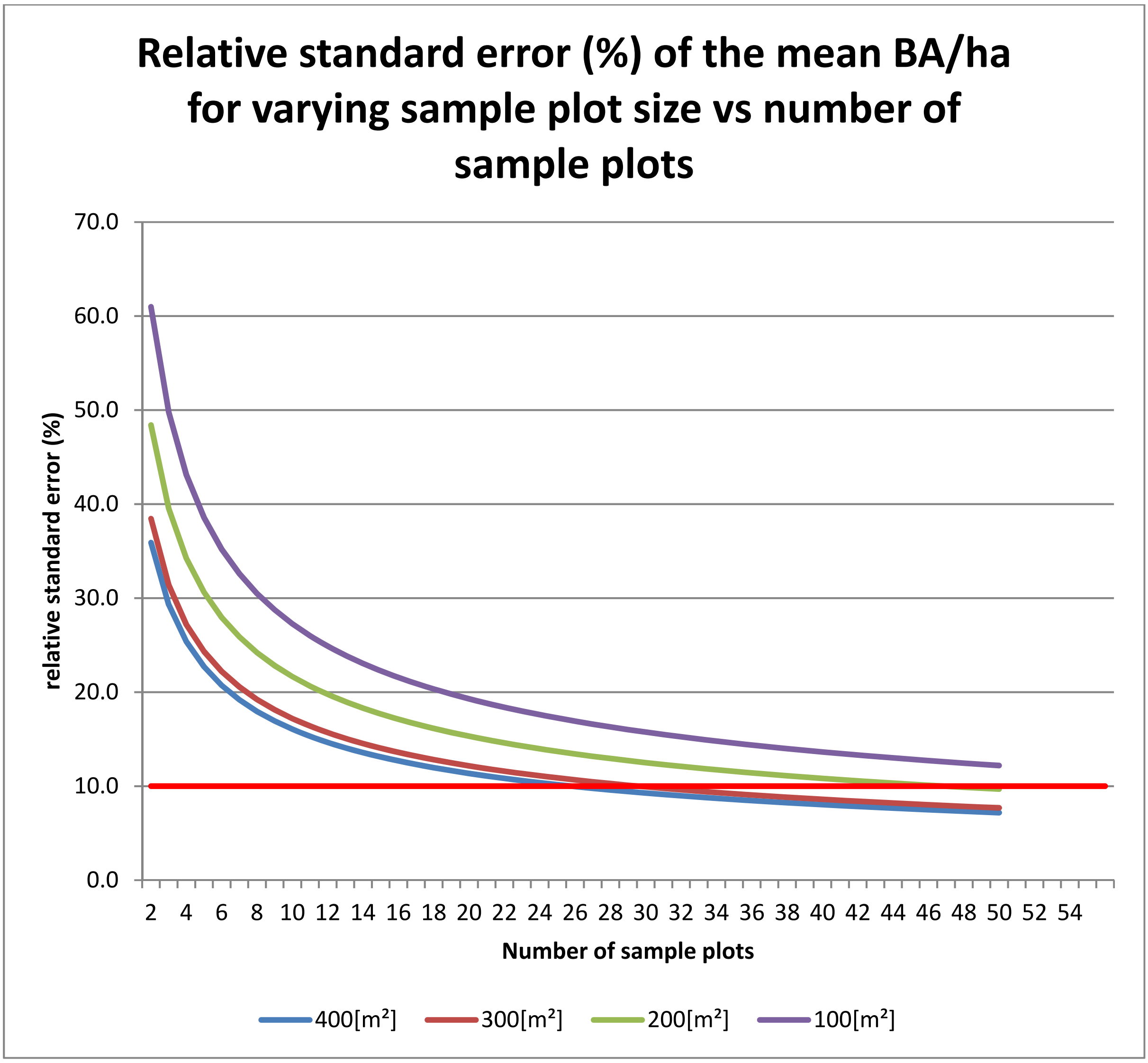


Figure 34: Relative standard error of the mean basal area per hectare for varying sample plot size (400 m^2, 300 m^2, 200 m^2, 100 m^2) for a range of sample plots (2 – 50) on the study site

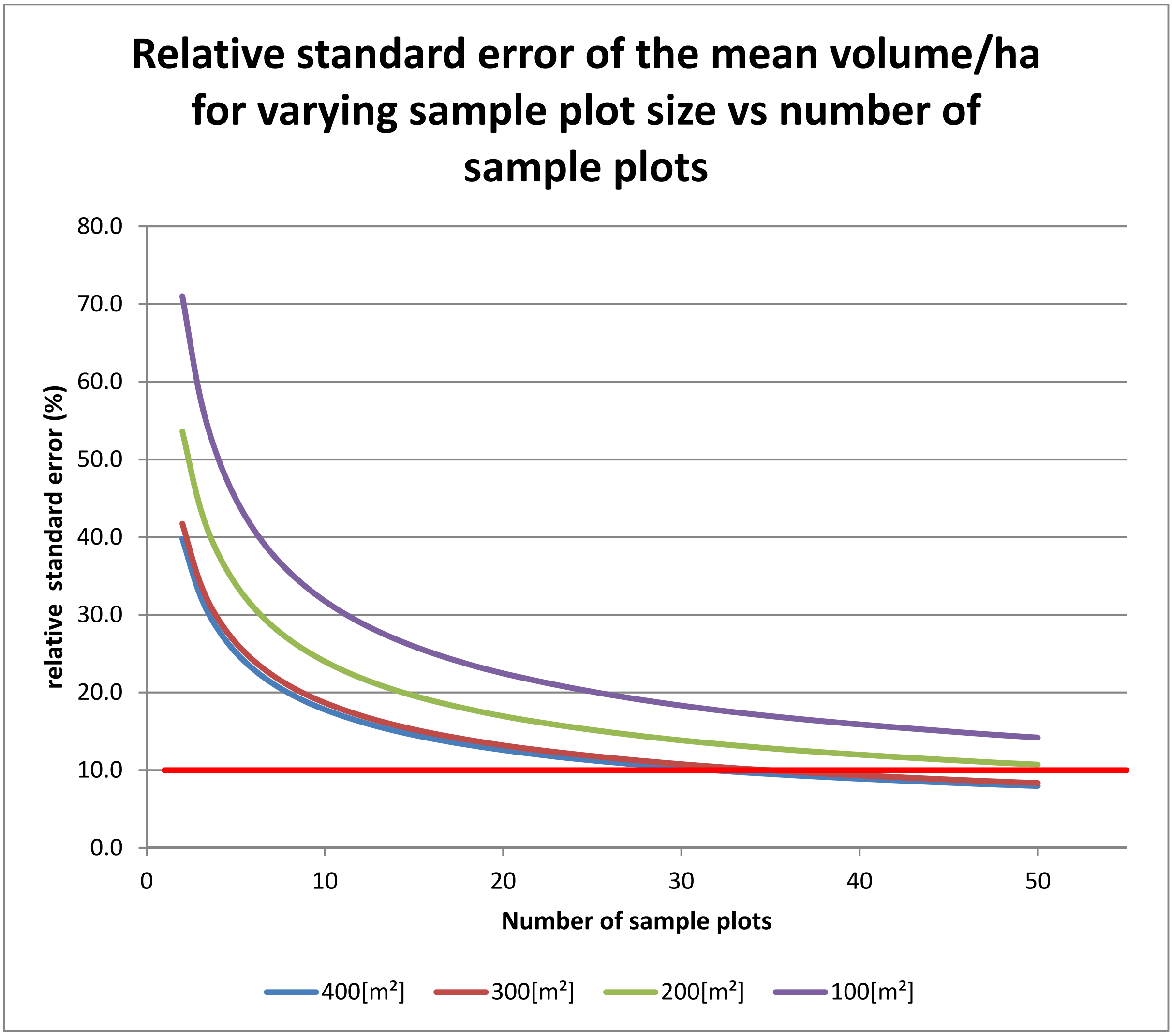


Figure 35: Relative standard error of the mean volume per hectare for varying sample plot size (400 m^2, 300 m^2, 200 m^2, and 100 m^2) for a range of sample plots (2 – 50) on the study site

Table 29 below gives the number of sample plots required to achieve a desired relative standard error of 10% for mean BA per hectare (m^2/ha) and mean volume per hectare (m^3/ha). The relative standard error increases once a model is introduced – Schumacher and Hall standing volume function (Table 29, Figure 34 compared to Figure 35). To calculate volume using BA; meaning that to estimate volume precisely, more sample plots are required.

Table 29: Summary of the number of sample plots needed for varying sample plot size (400 m^2, 300 m^2, 200 m^2, 100 m^2) when considering mean BA per hectare and volume per hectare.

Sample plot size [m^2]	Number of sample plots at desired relative standard error 10%	
	Mean BA [m^2/ha]	Mean volume [m^3/ha]
100	74	101
200	47	57
300	30	35
400	26	32

The summary in Table 30 below presents the relative standard error calculation up to 22 sample plots (number of sample plots used in the inventory of the study site). The relative standard error values for 300 m^2 and 400 m^2 sample plots show a smaller difference than for 100 m^2 and 200 m^2 sample plot sizes. Evidently, using volume per hectare as indicator, the desired level of precision in the relative standard error (less than or equal to 10%) was not reached with 22 sample plots.

Table 30: Statistical summary for volume per hectare over 22 sample plots with varying sizes (400 m^2, 300 m^2, 200 m^2, 100 m^2) on the study site.

Volume/hectare				
Sample plot size (m^2)	400	300	200	100
n	22	22	22	22
Mean BA	247.48	259.23	290.26	332.14
Variance	19375.91	23409.35	48424.84	111221.32
Standard. Deviation	139.20	153.00	220.06	333.50
Standard Error	29.68	32.62	46.92	71.10
Relative Standard Error (%)	11.99	12.58	16.16	21.41

Analyses of the sampling method used in the inventory also suggest that a different sampling design should be used by NRM in future. An inventory intensity of 8.5% (area based) is low in comparison to South African plantation forestry norms (Howard, 2012). An inventory percentage of 10% or more is likely to be used in plantations when high levels of accuracy is required for estimates of high value timber (e.g. sawtimber or veneer) or harvest planning. It should be noted that more intense inventory percentages are also dependent on lower stand densities, normally fewer than 300. The study site has approximately 700 STPH, but the number of trees able to deliver high quality sawlogs is considerably lower than plantation forests (Stafford & Blignaut, 2017), meaning the recommendation to increase sampling intensity should still be considered valid. The layout pattern, number of sample plots, and size, should not be considered sufficient as it was unable to fully represent the variability of trees on the study site when considering the desired precision level and relative standard error calculation carried out in the sampling analysis.

The analysis indicated that the sample plot size and quantity would not have led to the required precision. The calculations showed that a sampling design of 35 plots with a size of 300 m^2 each employed in a systematic layout would have been the optimal sampling design. With this variation in sampling design it would be possible to achieve a relative standard error of maximum 10%. This was not possible with the applied sampling design. With these results, one can plan future inventory designs for invasive stands.

The patchy distribution of trees throughout the study site is shown in the number of trees found in each of the 22 sample plots (1 – 63), indicative of non-regular tree spacing. Furthermore, the diameter distribution resembles a reverse J-shape, indicative of the diameter distribution of unmanaged natural forests (Westphal, et al., 2006). If available, higher resolution satellite imagery of the study site and similar invasive sites NRM is already aware of can be used to isolate and exclude large open patches not occupied by trees. Site area extents can then be recalculated and new sampling layouts with new intensities can be designed capturing as many of the trees present on the site as possible (Watt & Watt, 2011). This would redefine the forested area, returning improved sample plot layout, reducing potential standing volume overestimation bias which could be introduced when ignoring sparse patches. NRM has already received remotely sensed data images (aerial photographs) of problem sites and perhaps in future more problem sites could be photographed, but with a higher resolution to find more accurate area extents (and therefore patchiness) of invaded areas and upscale to regional utilisable sawlog volume. If discernible, dominant stand height and species composition being parameters of interest. Currently, the resolution of scale corrected aerial photograph maps of NRM sites is 100 m x 100 m (Main, et al., 2016).

Chapter 5: Conclusions and Recommendations

This study has presented estimates of utilisable/recoverable volume relative to total standing volume for a range of five DBH classes, and for two tree species present on a single study site along the Berg River. Insightful information about the methods and level of data collection to derive the estimates and the error of the estimates is also presented. This site represented a good case study because it had already been identified by NRM as a site suitable for clearing with the potential to recover higher value sawn products. As part of the study, other sites were explored, and the categorisation of three broad types is a useful outcome. Further work extension of this study to other site types (not possible here for reasons previously given) would be a very useful outcome.

It is likely that “forest” type stands, of the sort studied in this study at “Paarl farm” represent potential cases for viable extraction of higher value sawlogs and subsequent products like boards for school desks produced by the VAI programme. Sawn product volume recovery of the mean sawlog in the form of boards for the manufacturing of school desks was tested for and presented for this particular site type.

However, the developed SVCF has shown that the riparian forest type the study is concerned with should not be regarded by NRM as capable of delivering higher value sawlogs only. The SVCF investigated stem form in more detail and caused a reduction in initial estimates of standing volume. The results show that height at first major branching influenced sawlog volume recoverable from the study site more so than taper did. Reductions of utilisable sawlog length were attributed to the height at which first major branching occurred. This position on the stem was used as the top cut-off point for sawlog length a tree could deliver. Crown length was found to be an important tree-level characteristic as the height difference between the start of the tree crown (first major branching) and top height influences recoverable sawlog length, and therefore sawlog volume.

5.1 Stem form

The SVCF has shown that, on average, sawlogs for utilisation in a sawmill environment represent a fraction of the total standing volume present on the study site. For *Acacia mearnsii*, on average across all five DBH classes, there is an expected decrease from total standing volume to sawlog volume of 25.33 %, delivering a sawlog volume of 11.73 m^3/ha. For *Eucalyptus camaldulensis*, on average across all five DBH classes, there is an expected decrease from total standing volume to sawlog volume of 23.54 %, delivering a sawlog volume of 144.69 m^3/ha.

Regarding sawn product volume recovery, the study has shown that for the limited range of defined products (boards) recovery is variable (20 % - 50%). This is due to various factors, as mentioned previously, but there is indeed potential for sawlogs recovered from the study site to be utilised in sawmills of the VAI programme. What these variable recovery percentages suggest is that logs of larger diameter (i.e. logs with small-end diameter greater than or equal to the minimum width of all boards – 110 mm, Table 3) should be used if sawing for the defined school desk boards only. Another alternative is to increase the number of products to saw for and to strive for more flexibility in the dimensions of these products. This will improve recovery percentage and convert more of a log's volume to sawn product, ultimately improving the cost to benefit ratio of the programme.

The results from stem sweep were also investigated for a select few trees on the example study site with sawn product volume recovery percentage tested. *Eucalyptus* logs with sweep were shown to experience decreased volume recovery percentages as opposed to those without sweep. This means that stem sweep should be minimised through bucking to extract and process the straightest possible logs in order to mitigate the effect of log sweep on sawn product volume recovery. The simulations have shown in the case of shorter *Acacia* logs, an improved volume recovery even with the presence of sweep. Minimising log sweep through bucking will decrease log length, but as the results have shown, a longer length of log is more likely to return a greater sweep value than a shorter length and therefore a greater loss in recoverable product volume than a shorter length.

5.2 Feasibility of forest inventory

In terms of forest inventory, this study has presented a research method which has the possibility of being implemented as a standard pre-harvest inventory (using the laser calliper), with emphasis on measuring higher value sawlogs in riparian AIFs. Angle count sampling (ACS) is a simpler method of forest inventory which will not provide estimates of higher value sawlogs, but can however be expected to provide estimates of standing volume through BA measurement. Laying out of sample plots is not a feature of ACS, and no losses in accuracy are experienced provided the method of tree sighting is carried out correctly. ACS has an advantage in data gathering speed over the sampling method used in this study (defined circular plots) (Bay, 1960).

Measurements of stand BA and mean height for input into standing volume models from ACS will not return information that NRM officials could use directly to understand a site's potential to deliver specifically higher value sawlogs (when compared to the detailed level applied in this study). But, NRM inspectors or contractors could still use ACS to gain a rudimentary understanding of the stand BA and standing volume as part of a pre-harvest inventory. Thereafter, if required, the use of laser callipers or taper models to gather further information about available sawlogs would not be impractical.

5.3 AIP biomass and sawlog suitability

While this study has shown that the extraction of high-value sawlogs for utilisation by the VAI programme is possible, the question remains if this is actually feasible. Logistical analyses of NRM clearing operations were briefly touched on in an introductory chapter explaining how the costs of clearing are discounted against biomass cleared to roadside by NRM contractors. Considering the low percentage of biomass deemed suitable for lumber from a region of NRM sites (Stafford & Blignaut, 2017), extraction of higher value sawlogs could be combined with operations clearfelling biomass for a range of uses. The ecological and socio-economic orientation of NRM's objectives are in-line with maximum utilisation of cleared biomass from a site. That said, sawlogs can be separated from cleared biomass and utilised accordingly, while remaining non-sawlog compliant biomass could be put to use elsewhere.

While the availability of AIP biomass for lumber is limited, the financial value thereof is in the highest category (section 2.1.1), further illustrating the value in this study's findings in terms of job creation possibilities for the VAI programme. A strong recommendation for future NRM research is to assess the feasibility of extracting biomass from riparian AIFs with the intention of separating the biomass into suitability classes satisfying the VAI programme's spectrum of end-uses. This will see maximum fulfilment of NRM objectives; socio-economic through the highest possibilities of job creation in the VAI programme, and ecological by the highest possibility of landscape restoration by clearing and utilising all biomass from an ear-marked site.

5.4 Expected contribution to MUCP

The MUCP software (section 1.4) is useful to NRM in that it can predict the reduction in invasive biomass density with each successive clearing operation, ultimately delivering a project culmination point, normally a few years in the future. What makes the software powerful is its ability to tailor each project to the land owner's specific needs or wants. NRM officials can approach land owners with information from studies like this one, incentivising these land owners to assist in payment for successive clearing operations themselves because of a guaranteed income. This will alleviate the annual cost burden falling on NRM and hopefully set a precedent for other land owners to follow in achieving NRM's ecological goals.

This study will contribute to the MUCP in that will give NRM officials more information about the potential value of standing trees on a riparian AIF. With a pre-harvest inventory, estimation of standing volume per species can be obtained, thereafter utilisable sawlog volume can be estimated using the results of this study's SVCF. The reduction from standing volume to sawlog volume can be estimated, on average (m^3/ha), for all trees on a site (i.e. all DBH classes, starting at minimum 7.5 cm), or it can be estimated for trees belonging to specific DBH classes if only these are deemed suitable sawlogs (e.g. larger trees; DBH > 26 cm).

Understanding the value of standing trees will deliver further insight into the costs and feasibility of clearing operations. This information can then be used in negotiations with harvesting contractors and down-stream VAI programme entities to decide on prices for delivered lumber.

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[Último acceso: September 2017].

Appendix: Simsaw 6 simulations settings

Simsaw Simulation Report : Board Piececount

(Ideal Logs)

Log class specifications

Log class no.	Diameter (cm) Min	Max	Length (m) Min	Max	Incr	Taper (mm/m) Min	Max	Sweep (mm/m) Min	Max	Ovality Min	Max	Defect core (%) Min	Max	Grade description	Log price (R/m³)	No. of logs
1	5.0	22.9	0.5	10.0	0.1	0.0	99.0	0.0	40.0	0.50	1.50	0	100	All log grades,	0.00	153
2	23.0	44.9	0.5	10.0	0.1	0.0	99.0	0.0	40.0	0.50	1.50	0	100	All log grades,	0.00	30
3	45.0	80.0	0.5	10.0	0.1	0.0	99.0	0.0	40.0	0.50	1.50	0	100	All log grades,	0.00	1

Grade Outputs

Log grade	Thickness (mm)	Width (mm)	Board grade	Precentage defect core 0 %	1-50%	51-99%	100%
All log grades		110.0	All board grades	100	100	100	100
		450.0	All board grades	100	100	100	100
			All board grades	100	100	100	100

Machine settings

1 Line 1

Primary Breakdown Machine
Kerf sizes (mm) : 3.0
Log rotation (deg) : 0
Log misalignment (mm) : 0
Saw offset (mm) : 0

Secondary Breakdown Machine
Kerf sizes (mm) : 3.0
Cant guiding : None
Cant misalignment (mm) : 0
Saw offset (mm) : 0
Min radius for RTC machine (m): 0.0 (0mm)

Edging
Edging for max : Volume
No of blades : 4
Kerf size (mm) : 3.0

Resaw
Primary : On
Kerf size (mm) :3.0
Secondary : On
Kerf size (mm) :3.0

Product specifications

Thicknesses (mm) Dry	Wet	Widths (mm) Dry	Wet	Lengths (m) Description	Min	Max	Incr	Combinations Thickness (mm)	Width (mm)	Length	Grade	Price (R/m³)
30.0	31.0	110.0	113.8	600 mm	0.6	10.0	0.6	30.0	110.0	600 mm	All board grades	7377.00
		450.0	465.8	700 mm	0.7	10.0	0.7	30.0	110.0	700 mm	All board grades	7377.00
				1100 mm	1.1	10.0	1.1	30.0	110.0	1100 mm	All board grades	7377.00

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1200 mm	1.2	10.0	1.2	30.0	110.0	1200 mm	All board grades	7377.00
1300 mm	1.3	10.0	1.3	30.0	110.0	1300 mm	All board grades	7377.00
				30.0	450.0	600 mm	All board grades	7377.00
				30.0	450.0	1200 mm	All board grades	7377.00

Wane specifications

Board dimensions (mm)		Maximum wane			
Thickness	Width	Thickness (%)	Width (%)	Length	Units
30.0	110.0	0.0	0.0	0.0	%
30.0	450.0	0.0	0.0	0.0	%

Board piececount results

Total log volume (m³) : 59.0669

Dry volume recovery (%) : 48.43
Wet volume recovery (%) : 51.86
Value recovery (R/m³) : 3573.05
Nett value recovery (R/m³) : 3573.05

Chips volume (m³) : 21.9315
Chips value (R/m³) : 0.00
Sawdust volume (m³) : 6.5019
Sawdust value (R/m³) : 0.00

Thickness (mm)	Width (mm)	Length (m) (m)	Grade	No of pieces	Volume (m³)	Value (R)	Volume %	Value %	Pieces %
30.0	110.0	0.6	All board grades	36	0.0713	525.83	0.2	0.2	2.1
30.0	110.0	0.7	All board grades	84	0.1940	1431.43	0.7	0.7	4.9
30.0	110.0	1.1	All board grades	31	0.1125	830.13	0.4	0.4	1.8
30.0	110.0	1.2	All board grades	26	0.1030	759.54	0.4	0.4	1.5
30.0	110.0	1.3	All board grades	25	0.1073	791.18	0.4	0.4	1.4
30.0	110.0	1.4	All board grades	75	0.3465	2556.13	1.2	1.2	4.3
30.0	110.0	1.8	All board grades	52	0.3089	2278.61	1.1	1.1	3.0
30.0	110.0	2.1	All board grades	8	0.0554	408.98	0.2	0.2	0.5
30.0	110.0	2.2	All board grades	40	0.2904	2142.28	1.0	1.0	2.3
30.0	110.0	2.4	All board grades	38	0.3010	2220.18	1.1	1.1	2.2
30.0	110.0	2.6	All board grades	53	0.4547	3354.62	1.6	1.6	3.1
30.0	110.0	2.8	All board grades	29	0.2680	1976.74	0.9	0.9	1.7
30.0	110.0	3.0	All board grades	54	0.5346	3943.74	1.9	1.9	3.1

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30.0	110.0	3.3	All board grades	52	0.5663	4177.45	2.0	2.0	3.0
30.0	110.0	3.5	All board grades	10	0.1155	852.04	0.4	0.4	0.6
30.0	110.0	3.6	All board grades	54	0.6415	4732.49	2.2	2.2	3.1
30.0	110.0	3.9	All board grades	46	0.5920	4367.33	2.1	2.1	2.7
30.0	110.0	4.2	All board grades	71	0.9841	7259.41	3.4	3.4	4.1
30.0	110.0	4.4	All board grades	81	1.1761	8676.24	4.1	4.1	4.7
30.0	110.0	4.8	All board grades	15	0.2376	1752.78	0.8	0.8	0.9
30.0	110.0	4.9	All board grades	39	0.6306	4652.16	2.2	2.2	2.3
30.0	110.0	5.2	All board grades	21	0.3604	2658.38	1.3	1.3	1.2
30.0	110.0	5.4	All board grades	6	0.1069	788.75	0.4	0.4	0.3
30.0	110.0	5.5	All board grades	23	0.4174	3079.53	1.5	1.5	1.3
30.0	110.0	5.6	All board grades	48	0.8870	6543.69	3.1	3.1	2.8
30.0	110.0	6.0	All board grades	58	1.1484	8471.75	4.0	4.0	3.4
30.0	110.0	6.3	All board grades	40	0.8316	6134.71	2.9	2.9	2.3
30.0	110.0	6.5	All board grades	21	0.4504	3322.97	1.6	1.6	1.2
30.0	110.0	6.6	All board grades	101	2.1998	16227.78	7.7	7.7	5.9
30.0	110.0	7.0	All board grades	28	0.6468	4771.44	2.3	2.3	1.6
30.0	110.0	7.2	All board grades	59	1.4018	10341.37	4.9	4.9	3.4
30.0	110.0	7.7	All board grades	2	0.0508	374.90	0.2	0.2	0.1
30.0	110.0	7.8	All board grades	94	2.4196	17849.09	8.5	8.5	5.4
30.0	110.0	8.4	All board grades	11	0.3049	2249.39	1.1	1.1	0.6
30.0	110.0	8.8	All board grades	23	0.6679	4927.25	2.3	2.3	1.3
30.0	110.0	9.0	All board grades	4	0.1188	876.39	0.4	0.4	0.2
30.0	110.0	9.1	All board grades	83	2.4925	18387.10	8.7	8.7	4.8
30.0	110.0	9.6	All board grades	27	0.8554	6309.99	3.0	3.0	1.6
30.0	110.0	9.8	All board grades	5	0.1617	1192.86	0.6	0.6	0.3
30.0	110.0	9.9	All board grades	142	4.6391	34222.94	16.2	16.2	8.2
30.0	450.0	2.4	All board grades	11	0.3564	2629.16	1.2	1.2	0.6
				1726	**28.6090**	**211048.74**			

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